PROCEEDINGS

2007 USCID Fourth International Conference on Irrigation and Drainage

The Role of Irrigation and Drainage in a Sustainable Future

USCID

The U.S. society for irrigation and drainage professionals

The Role of Irrigation and Drainage in a Sustainable Future

USCID Fourth International Conference on Irrigation and Drainage

Sacramento, California
October 3-6, 2007

USCID
The U.S. society for irrigation and drainage professionals

Edited by

Albert J. Clemmens
Agricultural Research Service, USDA

Susan S. Anderson
U.S. Committee on Irrigation and Drainage

Published by

U.S. Committee on Irrigation and Drainage
1616 Seventeenth Street, #483
Denver, CO 80202
Telephone: 303-628-5430
Fax: 303-628-5431
E-mail: stephens@uscid.org
Internet: www.uscid.org

Proceedings Sponsored by the Bureau of Reclamation

USCID

The Mission of the United States Committee on Irrigation and Drainage is to foster sustainable, socially acceptable and environmentally responsible irrigation, drainage and flood control systems and practices for providing food, clothing and shelter to the people of the United States and the World.

USCID is a nonprofit professional society whose members share an interest in the planning, design, construction, operation and maintenance of irrigation, drainage and flood control works; agricultural economics; water law; and environmental and social issues affecting irrigated agriculture.

USCID is the United States member of the **International Commission on Irrigation and Drainage** (ICID), an association of more than 70 countries. Founded in 1950, ICID is a non-governmental organization dedicated to the sound and responsible management of water resources. Its central purpose is to promote the development and application of the sciences and techniques of irrigation, drainage, flood control and river channel stabilization.

USCID publishes the *USCID Newsletter*, proceedings of USCID meetings and special reports; organizes and sponsors periodic technical meetings and Conferences; and distributes ICID publications.

Since 1986, USCID has organized a number of regional, national and international meetings throughout the U.S. These meetings address contemporary issues affecting irrigated agriculture, offering a multi-disciplinary evaluation of problems and solutions.

For additional information about USCID, its meetings, publications and membership, contact

USCID
1616 Seventeenth Street, # 483
Denver, CO 80202
U.S.A.

Telephone: 303-628-5430
Fax: 303-628-5431
E-mail: stephens@uscid.org
Internet: www.uscid.org

Printed in the United States of America

Library of Congress Control Number: 2007936313

ISBN 978- 1-887903-23-3

Preface

The papers included in these Proceedings were presented during the **USCID Fourth International Conference on Irrigation and Drainage**, held October 3-6, 2007, in Sacramento, California. The Conference was held in conjunction with the 58th International Executive Council Meeting of the International Commission on Irrigation and Drainage. An accompanying book presents abstracts of each paper. The theme of the Conference was ***The Role of Irrigation and Drainage in a Sustainable Future***.

Developing and managing the world's water resources has become more complex and more challenging than ever before. In addition to the fundamental need for water to support life and the environment, humans use water as an essential input in producing food and fiber and in many other productive processes. The demand for water is increasing as the world's population moves beyond six billion and as standards of living improve across Asia and in many regions. Higher incomes lead to increasing demands for goods and services that involve water in their production. In addition, we are belatedly realizing that human uses of water can degrade water quality and damage the environment. As a result, the pressure on our finite water resources is immense.

Irrigation is the principal use of water in many regions. Around the world, farmers are being challenged to produce more food with less water, while also reducing harmful impacts on the environment and sharing water with cities and industries. These goals can be achieved with improved management of irrigation and drainage systems.

USCID's Fourth International Conference provided a forum to discuss the many issues related to the role of irrigation and drainage in a sustainable future. Oral presentations were made during 15 concurrent Technical Sessions; additional papers were presented during a Poster Session.

Papers were accepted in response to a call for papers. The authors are professionals from academia; many foreign government agencies, as well as federal, state and local U.S. government agencies; water and irrigation districts; and the private sector. More than two dozen countries are represented.

USCID and the Conference Chairman express gratitude to the authors, session moderators and participants for their contributions.

The Office of International Affairs, **Bureau of Reclamation** sponsored the Conference Proceedings and this support is acknowledged with appreciation.

Albert J. Clemmens
Agricultural Research
Service, USDA
Maricopa, Arizona

Conference Chairman

Contents

Advances in Estimation of Evapotranspiration

Using Recycled and Poor Quality Water for Irrigation

Irrigation Project Operations

Management of On-Farm Irrigation Systems

Technical Advances in On-Farm Irrigation Methods

Adapting to Limited Water Supplies in Australia

Adapting to Increasing Competition for Water

Innovative Approaches to Irrigation Management

Increasing Competition for Water — Irrigation vs Urban Uses

Technical Advances in Irrigation System Operations

Water Supply Sustainability

Poster Session

INTEGRATED REGIONAL WATER MANAGEMENT: THE NEW DIRECTION IN CALIFORNIA

Steve Macaulay, P.E.[1]
Francis Borcalli, P.E.[2]

ABSTRACT

Water resource planning is approached classically on a project-by-project basis, with an increasing trend towards multiple-benefit projects. Multiple-jurisdiction projects have been more the exception than the rule, largely due to a lack of shared interests, time lines, financing and other factors. Integrated regional water management (IRWM) is a recent phenomenon in California. This concept embodies the integration of a wide range of strategies, management tools and institutions to address water supply reliability, ecosystem enhancement, water quality and other natural resource issues. The IRWM focus is on addressing areas of common concern among a number of interests within a region, whether that region is defined by political, institutional or watershed boundaries. It has proven to be a successful strategy driven by development and population increases, a growing interest in protecting natural species habitat, and the need to diversify water supplies to strengthen water supply reliability for all uses.

This paper describes the evolution of IRWM, from successful programs initiated at the local level to endorsement of the concept for statewide use in the 2005 California Water Plan Update. The paper addresses how the State of California is encouraging IRWM at both the policy and funding levels. We provide an overview of current IRWM planning and implementation throughout California. The Yolo County IRWM Plan is a case study of a successful collaborative effort to enhance water supply reliability —quantity and quality — for urban, agricultural, environmental, and recreational uses while addressing a range of issues related to ecosystem enhancement, flood risk management, and recreation.

BACKGROUND, CALIFORNIA WATER DEVELOPMENT & MANAGEMENT

California is located on the west coast of the United States, and has a Mediterranean climate with warm dry summers and cool wet winters. Most of our rainfall is in northern California, and most of our population is in southern California. We have more than 9 million acres of irrigated farmland, and a population of 35 million people. The general location of the State of California is shown in Figure 1.

[1] Vice President, West Yost Associates, 1260 Lake Blvd, Suite 240, Davis, CA 95616 Phone – (530) 756-5905 Fax ----- (530) 756-5991 Email: smacaulay@westyost.com. Serves also as Executive Director, California Urban Water Agencies.
[2] Manager, Water Resources Department, Wood Rodgers, Inc., 3301 C Street, Building 100 B, Sacramento, CA 95816 Phone – (916) 326-5224 Fax ----- (916) 341-7767 Email: fborcalli@woodrodgers.com

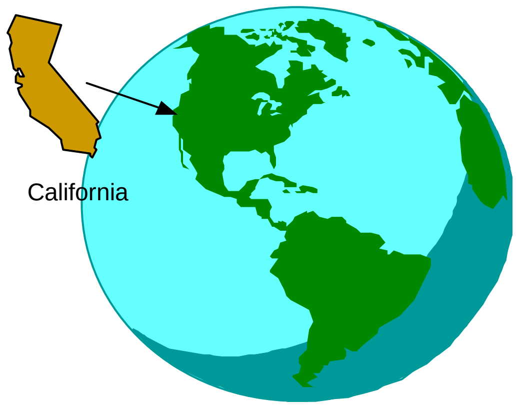


Figure 1. Location of State of California, United States

Water Development

Water resources development has gone through significant changes in California over the past 150 years. Initial water projects were constructed by landowners or small communities to meet their needs: irrigation, gold mining and drinking water. As population increased in larger centers such as Los Angeles and San Francisco, larger projects were developed to bring domestic water supplies from hundreds of miles away. These large projects early in the 20th century were largely single purpose: to meet the needs of growing communities. Several decades later saw the development of multipurpose projects, largely for urban and agricultural water supplies but incorporating hydropower generation, recreation, flood control and fishery benefits. These projects – transferring water from east to west and north to south, were essential in the development of California's economy and large urban areas.

Figure 2. California's Developed Water Systems

California and much of the United States went through an environmental awakening beginning in the 1960s, resulting in a new "water ethic" and passage of many federal and state laws providing a greater level of environmental protection as it related to water projects. The next major change came about as the result of a prolonged drought in California from 1987 through 1994.

Much of California's developed water supplies are withdrawn from the Sacramento-San Joaquin Delta, a tidal estuary east of San Francisco Bay at the confluence of the Sacramento and San Joaquin rivers. The drought seriously affected water supplies and the fisheries associated with the Delta. One of the consequences was greatly reduced water supply reliability to protect endangered fish species. Another was the development of market-based water transfers in response to the drought-induced statewide water supply crisis. Ultimately the drought and its impacts resulted in the creation of a comprehensive federal/state partnership, the CALFED Bay-Delta Program (CALFED), to deal with the water supply, quality, flood control and ecosystem problems of the Delta on a more comprehensive basis.

Figure 3. Sacramento-San Joaquin Delta

Growing Water Supply Reliability Concerns

But the development of CALFED did not address the growing water supply reliability problems in different regions throughout California. Each region has its own environmental conflicts, water supply reliability challenges for both agricultural and urban use, and increasing regulatory restrictions affecting discharges from wastewater treatment facilities. There are also conflicts between urban and agricultural uses.

California water development for most of the 20th century focused on providing a reliable backbone water distribution system – both in its initial construction and subsequent operational challenges. Early in the 1990s – forced by the multi-year drought and other challenges -- different regions began experimenting with more comprehensive ways of solving water and other resource problems. The early 1990s saw a much more explicit relationship between urban and agricultural water uses than California had recognized in the past. The creation of the Governor's Drought Emergency Water Bank saw the flow of $100 million to farmers and more than 800,000 acre-feet of water from farms to cities in this large-scale, one year market reallocation experiment. There was a great deal of interest in large-scale agriculture-to-urban transfers, and a number of papers were presented at water conferences for several years during this period (including papers given at USCID and ICID conferences by one of the authors).

Those experiences formed one of the bases for developing the concept of integrated water management, recognizing that connecting urban and agricultural supplies in various ways could contribute to the water supply reliability of both uses.

The drought water bank was not the only example of a comprehensive regional approach. In 1996 one of the world's largest wholesale water agencies – the Metropolitan Water District of Southern California (MWD) – developed and adopted an Integrated Resources Plan. That plan was very comprehensive in nature, and expanded classic water planning to a broad array of water management options. A number of years of experience in implementing new conservation, recycled water and groundwater banking programs led to revisions of the plan in 2003. The 2003 plan set revised performance targets for conservation and recycled water use for the year 2020.

Integrated Regional Water Management

While the MWD plan was comprehensive in scope and geography, it covered many different watersheds with a "broad brush" approach. The next obvious approach was a focus at the watershed level. The Santa Ana Watershed Project Authority (SAWPA) developed a comprehensive program for management of water supplies and salinity that served as an important model of a successful regional partnership. The new approach SAWPA brought to the table is reflected in its name: a watershed approach to solving problems. This 2800 square mile watershed in southern California has a population of more than 5 million people. Over the past 50 years – and particularly in the past decade – this region has developed aggressive water management programs including artificial groundwater recharge, state-of-the-art water conservation and recycling programs, brine lines to manage salinity within the basin, desalination facilities, and injection wells along the Pacific coast to provide a hydraulic barrier to groundwater salinity intrusion. What makes this example unique is the cooperation of institutions within the basin, proving successful in setting aside litigation in favor of on-the-ground accomplishments. The region has also been very successful in acquiring several hundred million dollars of state and federal funds, largely due to strong regional institutions with common goals.

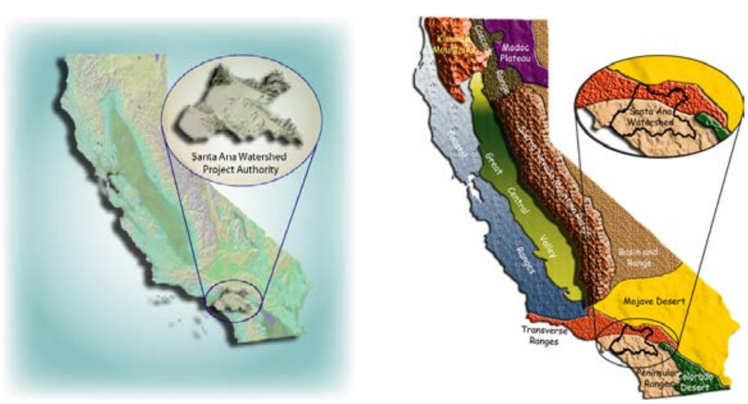


Figure 4. SAWPA location, Santa Ana River watershed

Throughout the 1990s it became increasingly clear that many of the actions needed to improve water supply reliability at the local level needed to be region-wide actions. A more formal Integrated Regional Water Management (IRWM) model came to be the new concept in advancing water resources management and development. It developed from a variety of successes and failures, at both the State and local level. In 2002 California voters approved a USD $4.6 billion bond measure, Proposition 50, which for the first time encouraged the development of IRWM plans (IRWMP). "Integrated" was intended to apply to: (1) different types of water use, (2) a range of water resource management tools, (3) a range of resource categories in addition to water, and (4) a range of local and regional institutions. Regions were not defined in Proposition 50, leading to a trial-and-error approach of self-selecting regions by the participants of individual IRWMPs. The California Department of Water Resources (CDWR) developed guidelines for allocating bond funds, allowing any three entities to form their own region as long as at least two of the entities were public agencies. In mid-2005, CDWR allocated Proposition 50 bond funds for development of IRWMPs. Each self-defined region took a different approach, developing its own unique blend of geography, hydrology, resource conflicts and institutions. Proposition 50 provided funds for development of the plans (up to $500,000 per plan), and also included more than $400 million towards implementation.

2005 Update, California Water Plan

From 2001 through the end of 2005, CDWR developed a major update to the California Water Plan, originally completed in 1957 and updated every five years. The 2005 Update has a strong emphasis on integrated approaches to solving water resources problems, and recommended effective leadership roles at the regional level. Although different hydrologic regions were evaluated in the 2005 Update, there were no clear recommendations as to how IRWMPs were to be defined by region. The 2005 Update concluded that more efficient use of water had the most promise, but that a full range of water management tools were needed to meet California's long-term agricultural, urban and environmental needs. Information from the 2005 Update is shown in the figure below, summarizing the water management strategies and their promise in contributing to water supply reliability.

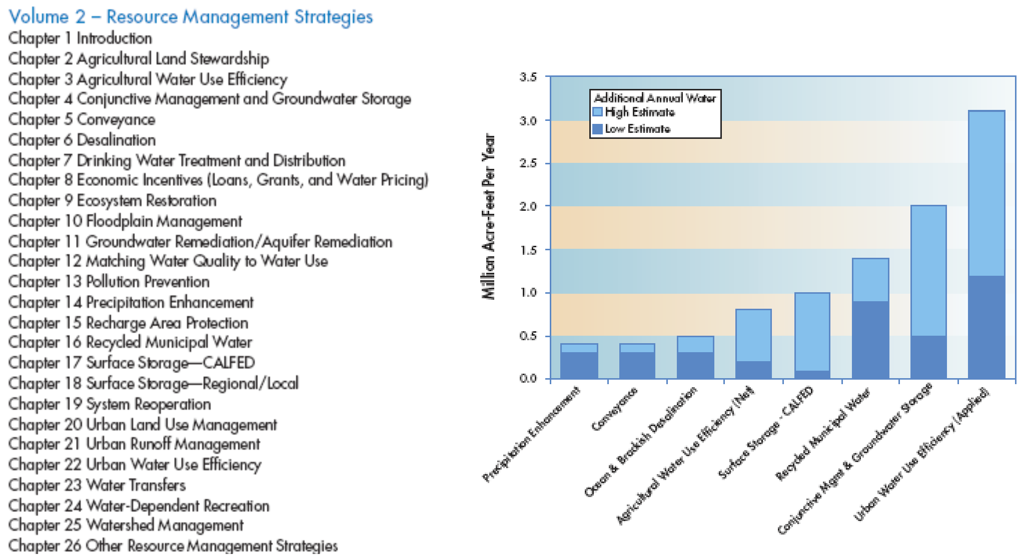


Figure 5. 2005 Water Plan Update, Resource Management Strategies and Potential for Increasing California Water Supplies

The 2005 Update's top two recommendations were to diversify regional water portfolios and promote and practice integrated regional water management. The 2005 Plan's "Framework for Action" identified how IRWM should fit in the state's overall water resources action plan. A graphic from the 2005 Update is reproduced in the figure below.

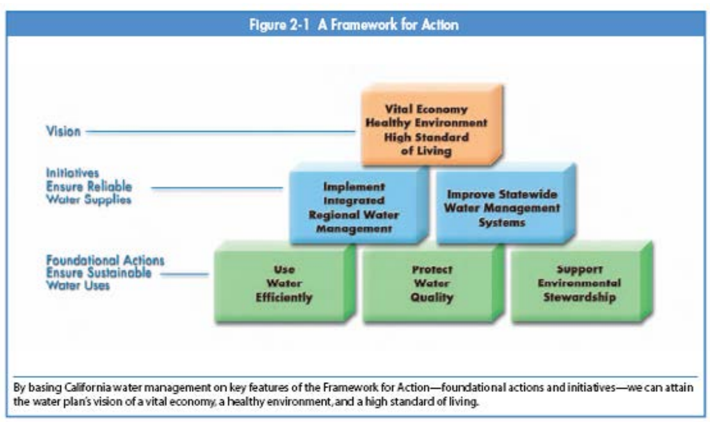


Figure 6. California Water Plan 2005 Update, Framework for Action

The initial experiences in dealing with integrated regional water management issues through Proposition 50 implementation were largely positive, although it was clear that self-selection of regions was institutionally awkward and not the most efficient use of bond funds. These experiences led to an expanded and more specific program in a subsequent bond issue that went before the voters in the November 2006 election. Proposition 84 passed overwhelming along with several other infrastructure investment bonds. Proposition 84 defined the regions on a hydrologic basis and apportioned USD $1 billion among the regions using population as a predominant (but not sole) factor.

As of late 2006 IRWM had been established as the strong policy direction from state government, and supported through bond funds approved by California voters. Integrated Regional Water Management Plans have been and are being developed throughout the state, from the large agricultural region of the Sacramento Valley to a comprehensive plan for urban and agricultural uses in San Diego County at the southern end of the state. Each is using the same IRWMP guidelines and management components and tailoring them to their respective regions' unique institutional, hydrologic and infrastructure conditions.

Required elements of California's Integrated Water Management Plans include the following:

- protecting communities from drought
- protecting and improving water quality
- improving local water security by reducing dependence on imported water

Examples of potential projects include (California Water Code Section 79561):

- *Programs for water supply reliability, water conservation, and water use efficiency;*
- *Storm water capture, storage, treatment, and management;*
- *Removal of invasive non-native plants, the creation and enhancement of wetlands, and the acquisition, protection, and restoration of open space and watershed lands;*
- *Pollution reduction, management, and monitoring;*
- *Groundwater recharge and management projects;*
- *Contaminant and salt removal through reclamation, desalting, and other treatment technologies;*
- *Water banking, water exchange, water reclamation, and improvement of water quality;*
- *Planning and implementation of multipurpose flood control programs that protect property; and improve water quality, storm water capture and percolation; and protect or improve wildlife habitat;*
- *Watershed management planning and implementation; and*
- *Demonstration projects to develop new drinking water treatment and distribution methods.*

YOLO COUNTY – A CASE STUDY

Yolo County (County) is located in the Sacramento Valley on the west side of the Sacramento River opposite the City and County of Sacramento in Northern California, and encompasses 653,370 acres (Figure 7). The County is home to over 175,000 people with nearly 85 percent of the population living in the four cities of Davis, West Sacramento, Winters, and Woodland. The eastern two-thirds of the County consists of nearly level alluvial fans, flat plains, and basins, while the western one-third is largely composed of rolling terraces and steep uplands used for dry-farmed grain and range. The elevation ranges from slightly below sea level near the Sacramento River in the southern part of the County to 3,000 feet along the ridge of the western mountains.

Figure 7. Sacramento Valley and Yolo County

The average annual precipitation varies from approximately 36 inches along the ridge of the western mountains to approximately 18 inches on the east side of the County in the vicinity of Woodland and Davis and the Sacramento River. All precipitation in the County occurs as rainfall. Occasionally, precipitation, as snow, occurs on the mountain ridges in the western part of the County, but melts within days.

Agriculture is the County’s primary industry and its gross valuation in 2005 was $332.7 million. Processing tomatoes is the County’s leading commodity and represents 21 percent of the total agricultural valuation. The total taxable sales in the County in 2005, of nearly $3.1 billion, represented 0.6 percent of the total taxable sales for California.

History of Water and Related Resources Planning

As a result of the foresight of early residents of the County, the investment of their time, energy, and monies paid significant dividends in creating a favorable water supply situation for beneficial uses in the County. The portfolio of water supplies consists of settlement and water service contracts with the U.S. Bureau of Reclamation for water from the Sacramento River, pre-1914 and appropriated water rights from the Cache Creek system, and a small increment of water from the Solano Project (Lake Berryessa) on Putah Creek. The last increment of water developed for use in the County was the Indian Valley Dam and Reservoir Project that was completed in 1975. On average, nearly 1 million acre-feet of water is applied for municipal, agricultural, and domestic uses with 60 to 40 percent being supplied from surface water depending upon the particular water year and the balance being provided from groundwater supplies.

Although the County was equipped with a favorable water supply as a result of agencies and individuals acting alone, the need to coordinate water resources activities among the various water purveyors (Figure 8) and those having land use authority in Yolo County was recognized by leaders in the community.

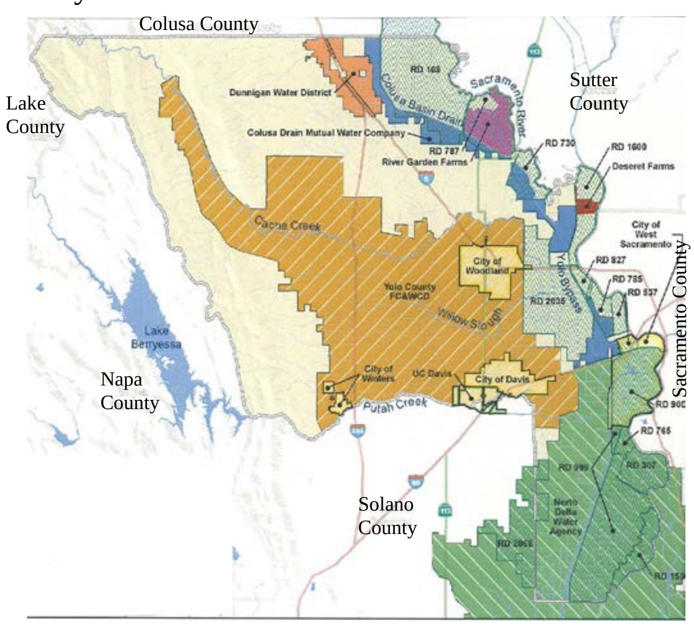


Figure 8. Water Agencies in Yolo County

In 1981, the preparation of the first countywide water plan was initiated. The "Yolo County Water Plan – 1984" was funded by two entities and adopted by the Yolo County Board of Supervisors in December 1984. This effort represented the first attempt to have water purveyors and the County at the same table to address water resource issues and needs within their respective jurisdictions. A good deal of attention was devoted to discussing the merits or benefits of interagency coordination and implementing activities that were deemed important to understanding and managing water resources within the County. The activities were directed at developing new increments of water to enhance water supply reliability, monitoring to better understand the surface and groundwater resources, and investigating water needs for land beyond the jurisdiction of any existing water purveyor, but potentially significant to the economy of the County. The time to complete the water plan was not driven by the technical elements of the work, but by the time required to get the respective parties to begin communicating about existing and future water-related matters without feeling that their "turf" was being threatened by the activities of another entity. After extensive reviews and edits all parties finally accepted forwarding the water plan to the Board of Supervisors for consideration and adoption.

The water plan included a recommendation to execute an Agreement for Water Management Coordination among the participating agencies and establish an Interagency Water Management Coordinating Group (Coordinating Group). The Agreement was never executed; however, the Coordinating Group, comprised of senior-level staff of participating agencies, was established on an informal basis. Where an agency did not have personnel there was no on-going participation. The Coordinating Group convened on a regular basis and through that process established a good working relationship and implemented some investigative work, although to a large extent independent of each other.

In 1991, the Coordinating Group recognized the need to update the water plan and elevate the overall awareness of elected officials and the public to water issues confronting California and Yolo County as well. Eight agencies participated in funding the water plan update, reflecting a much broader awareness and interest than existed in 1980. In 1992, the "Yolo County Water Plan Update – *To be effective it must be implemented*," was adopted by the Board of Supervisors and supported by the participating entities. Most of the activities outlined in the 1984 water plan remained to be performed and were highlighted in the Water Plan Update.

The Water Resources Association of Yolo County (WRA) was created as an outcome of the 1992 Water Plan Update. A Memorandum of Understanding was executed by: (1) the cities of Davis, West Sacramento, Winters, and Woodland; (2) the Dunnigan Water District; (3) the University of California at Davis; (4) Yolo County; and (5) the Yolo County Flood Control & Water Conservation District. There is a standing invitation for other water purveyors to participate, and Reclamation District No. 2035 recently joined. By design, the WRA was not established to be an implementing entity but rather to provide a forum for coordinating water resource related activities among member agencies, and to facilitate educating elected officials on water resource issues of interest at the local, regional and statewide levels. For a number of years the accomplishments of the WRA were limited and the viability of the WRA and the wisdom for it to continue was questioned. The member agencies were making significant accomplishments in implementing groundwater and land subsidence monitoring programs as well as special studies and investigations, several of which were funded by the Local Groundwater Assistance Program (AB 303) administered by the CDWR. Nevertheless, the usefulness of the WRA remained to be demonstrated. From time to time the idea of a countywide water agency emerged; however, it had never been articulated as to what its purpose would be or how problems would be resolved that the existing institutional structure could not handle.

Collaboration to Develop an IRWMP

As described earlier, the concept and impetus for IRWM can be credited to the CDWR. The opportunity to develop an IRWMP with funding provided by the CDWR was viewed by some WRA member agencies as an opportunity to determine the usefulness of the WRA. In March 2001, the WRA and the CDWR agreed to "…cooperatively plan an integrated resources management program identifying potentially feasible opportunities, initiatives, programs, or projects to improve water supply reliability in Yolo County." As a result of the agreement -- formalized in a Memorandum of Understanding -- the CDWR and the WRA committed to completing a countywide IRWMP.

The IRWMP was to update the County's 1992 water plan and, in so doing, explore opportunities for cooperative action, serve as a countywide forum to identify and address concerns related to water supply and drought preparedness; water quality; storm drainage and flood control; aquatic and riparian ecosystem enhancement; and recreation. Additionally, the process was to help provide a framework under which local water management policies, projects, and programs could be formulated, evaluated, and implemented.

The IRWMP was developed in two phases. The first phase focused on collecting technical information leading to an improved understanding of the County's water resources issues and concerns. The second phase was to utilize the information from Phase 1 to formulate and evaluate potential policies, programs, and projects needed to effectively address the identified issues and concerns. The first phase was completed in May 2005, with the results presented in the document titled, "Yolo County Integrated Regional Management Plan Background Data and Information Appendix."

Developing the IRWMP (Phase 2)

Preparing Phase 2 of the IRWMP was contingent upon the success of the WRA in receiving a planning grant under the Proposition 50 grant program administered by the CDWR. It was an expressed preference on the part of the CDWR for the "Region" to be geographically as large as practical. In the case of Yolo County, the region, for purposes of preparing the IRWMP, was deemed to be the County. It was the WRA's position that it was not yet prepared to participate in a meaningful dialogue with neighboring regions. It had a great deal of "homework" to perform before expanding the region beyond the County boundary. The CDWR accepted the WRA's justification of the region being limited to the County at this time, and the WRA was awarded a planning grant.

The preparation of the IRWMP was administered through the Technical Committee (TC) of the WRA, comprised of management and senior personnel of the respective member agencies. The TC, in collaboration with a consultant team, worked together closely to develop the IRWMP.

Drawing from data and information presented in the Background Data and Information Appendix (Phase 1), water resource plans, technical studies, and expressed public concerns spanning more than 20 years, the TC identified particular findings and issues related to the respective water resource management categories noted below.

- Water Supply and Drought Preparedness
- Water Quality
- Flood Management and Storm Drainage
- Riparian and Aquatic Ecosystem Enhancement
- Recreation

A significant change in planning for the IRWMP in relation to previous planning efforts is the attention given to planning for habitat enhancement and recreation from a resource perspective rather than from a mitigation perspective.

The TC and consultant team formulated actions, some that have been around for several years and some new, to address the resource issues. More than 160 actions were identified. These actions fell into two main categories: "foundational actions" and "individual actions," which directly address resource management issues. The foundational actions are projects or programs that form a foundation for resource management and are important regardless of the IRWMP. Foundational actions include planned or existing on-going studies, modeling projects, monitoring programs, or basic data-gathering activities. Individual actions are projects or programs that address resource management issues directly.

The County is comprised of a complex set of geographic subareas derived from hydrographic units that originate outside the County, as well as some that are contained within the County. Presented on Figure 9 are the geographic subareas of the County that guided the formulation of integrated projects for the IRWMP.

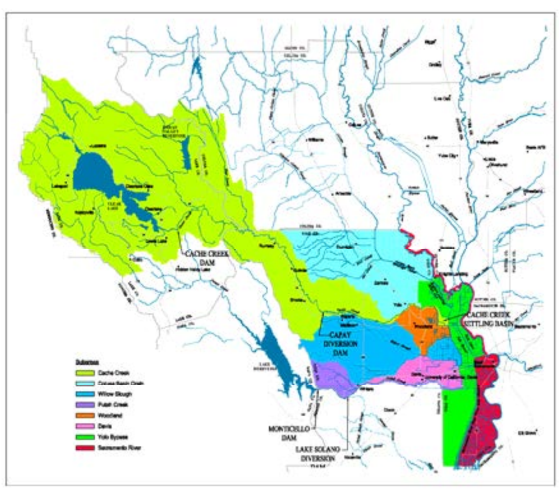


Figure 9. Yolo County IRWMP Geographic Sub-areas

Implementing programs and projects outlined in the two previous water plans was limited. Accordingly, the WRA, in initiating the preparation of the IRWMP, was intent on implementing projects and programs to address the issues of highest priority. With respect to implementation, it became readily apparent that the chances for success would be highest if integrated actions were formulated according to geographic subareas. Also, the leadership for implementing the respective integrated projects would need to be provided by the agencies or entities currently having jurisdiction, operations, or programs in the respective subareas. Eight integrated projects were formulated that included all actions specifically applicable to the area. The eight integrated projects are as follows:

1. Davis-Woodland Water Supply Project.

   The lead partners are the cities of Davis and Woodland and the University of California. They are working together to pursue implementation of a new surface water diversion from the Sacramento River and regional water treatment plant to perfect a 45,000 acre-foot water appropriation under the watershed of origin provisions of the California Water Code.

2. Reclamation District No. 2035 Sacramento River Diversion and Conveyance Project.

   The lead partner is Reclamation District No. 2035. It has completed construction plans and specifications to replace its pumped diversion from the Sacramento River with a new pumping plant with state-of-the-art fish screens. This project has the potential of being integrated with the Davis-Woodland Water Supply Project to share in the joint use of the new diversion.

3. Cache Creek Integrated Project.

   The lead partners are the Yolo County Flood Control & Water Conservation District, the City of Woodland, and Yolo County. A predominant activity in the integrated project is the risk of flooding to the City of Woodland from Cache Creek overtopping its banks and levees. Several other activities are incorporated in this integrated project that deal with conjunctive water use, environmental restoration, and recreation.

4. Dunnigan Integrated Project

   The lead partner is the Dunnigan Water District. The prospects exist as the County finalizes its General Plan for a new community with up to 10,000 new housing units. Central to this integrated project is the provision of water supply, wastewater, and storm drainage to accommodate planned growth while correcting water supply and wastewater issues that persist in the existing community.

5. Putah Creek Integrated Project.

   The lead partner is the Lower Putah Creek Coordinating Group. The Group has been effective in planning and implementing a wide range of instream and riparian habitat and environmental restoration projects and has plans for continuing this effort.

6. Yolo Bypass Integrated Project.

   The lead partners involve a wide range of stakeholders. The organizational structure is in its formative stages. The integrated project focuses on habitat restoration and management for waterfowl and fisheries while preserving the integrity of agriculture and the flood control function of the Yolo Bypass.

7. Sacramento River (West Bank) Integrated Project.

   The lead partners are the City of West Sacramento and Yolo County. Central to this integrated project is the flood protection afforded by the west bank of the Sacramento River and the integration of enhancement projects for environmental restoration and recreation.

8. Yolo County Sloughs, Canals, and Creeks Management Program.

   The lead partner is the Yolo County Flood Control & Water Conservation District. This integrated project is broad ranging geographically and involves the enhancement of water management and habitat associated with waterways on the west side of the County and the management of storm runoff resulting from rainfall originating within the County with respect to quantity and quality.

Although the WRA and its member agencies took the lead in preparing the IRWMP, it was recognized that implementation could be more effective if member agencies or organizations currently involved in planning and/or implementing projects and programs in the respective subareas assumed a leadership role for managing the implementation of the integrated projects. The WRA, in turn, would provide support in whatever manner was appropriate for the task. For implementing the eight integrated projects, the leadership or project management role for six of the projects was assumed by member agencies. For two of integrated projects, the Putah Creek Integrated Project and Yolo Bypass Integrated Project, the leadership was assumed by non-governmental agencies. With respect to Putah Creek, the planning and implementation of environmental restoration and enhancement projects has been underway for several years by virtue of a great deal of community involvement and the results of recent litigation that provided a funding source and organizational structure for managing activities along the creek. With respect to the Yolo Bypass, an informal working group has been meeting on a regular basis for several years; however, as it currently exists it is not suitable for more detailed planning and implementation of projects and programs. In this case, the WRA and the CDWR has encouraged and provided support to the working group to facilitate creating an organizational structure that would be equipped to implement programs and projects associated with the Yolo Bypass Integrated Project. Bringing structure to the group is proving to be a challenge; nevertheless, the process is underway.

The opportunity for public involvement was provided through three public workshops and the distribution of the draft IRWMP for public comment. Comments and input received on the draft IRWMP are being compiled and evaluated and the schedule is to have the final IRMWP presented to the WRA Board of Directors for adoption in late April 2007, and to the respective governing bodies of the member agencies for approval in May 2007.

SUMMARY

Integrated regional water management is the new force in California water resources development and management. California's water future will see greater integration of classic water management tools along with other resources. In the Yolo County example, considerable progress is now being made to advance the planning and implementation of many of the programs, and the relationships among the WRA member agencies has been strengthened through the IRWMP process.

To a large extent, institutional and technical challenges identified in the Yolo County IRWMP process are similar to those in other regions. Differences in geography and hydrology are important, but the existence of institutional challenges within regions appears to be universal (although specific areas of conflict or overlapping jurisdictions are unique to each region). Jurisdictional roles and responsibilities may not always be clear, and maintaining clarity and focus will be a challenge as personnel and politics change. California is gaining valuable experience in the development of regional water resource planning and management. This is expected to move the state forward toward diversifying water portfolios, advancing water supply reliability, and meeting the future needs of a diverse and growing population and economy.

While California's Proposition 50 bond funds and rules opened the door to state-funded IRWM plans, the experience indicated that self-selected regional boundaries will not work well for the future. The November 2006 Proposition 84 bond act provided an additional USD $1 billion of funding for IRWM implementation, but allocates the funds to ten large regions. The future challenge will be bringing the institutions together within each region to agree on apportionment of these funds, and a great deal of competition is expected. However, substantial benefits for the long term will be gained by the development of greater regional leadership for addressing our water problems.

ENVIRONMENTAL IMPACTS AND DRAINAGE WATER DISPOSAL CASE STUDY OF PAKISTAN

Bashir Ahmad[1]
Bashir Ahmad[2]

ABSTRACT

Pakistan possesses one of the largest contiguous irrigation systems in the world commanding about 16.7 Mha area. Intensive irrigation over a century has developed water logging and salinity problems in a major part of the command area. Unlike the contiguous irrigation network, Pakistan's drainage network is not interconnected. A number of Salinity Control and Reclamation Projects (SCARPS) have been constructed since 1960, which cover an area of 7.9 Mha. The existing drainage facilities comprise about 14,000 km of surface drains, 13,000 fresh ground water tube wells, 4,000 saline ground water tube wells and 12,500 km of sub-surface pipe drains. Drainage water disposal modes include reuse within the Indus Basin Irrigation System, disposal into Hamal Lake, Manchhar Lake & evaporation ponds and outfall into the Arabian Sea.

Although SCARPs, based on vertical drainage, did provide immediate relief, reuse of groundwater resulted in transportation of salts to the soil profile. In case of saline tube wells, the salts are being transported to lower riparian which are being ultimately added to soil profile as well as to groundwater. Disposal into evaporation ponds and lakes has also created severe environmental problems. Presently, only Left Bank Outfall Drain is available to transport surplus salts out of the Indus Basin. The overall salt balance is therefore negative, thus posing a serious threat to the sustainability of agriculture in Pakistan. For long term sustainability, salt balance of surface water, unsaturated root zone and saturated groundwater zone has to be maintained. The future strategy is therefore based on integration of drainage needs with water resource management, sub-surface pipe drainage and safe disposal of brackish drainage effluent into sea. The Government of Pakistan is already taking steps in this direction through implementation of the National Drainage Program.

In the southern province of Sindh, where groundwater is saline, a major on-going undertaking is lining of distributaries. Lining is also a major component in new irrigation projects like Greater Thal, Raini and Kachhi Canal systems, alongwith an ambitious program of water course lining, which is being implemented over the entire country. A project for high efficiency irrigation system i.e., Drip Irrigation & Sprinkler irrigation system is planned to be launched very shortly. For improving disposal of brackish drainage effluent from the left bank of Indus River into the sea, remodeling of the existing drain network is to commence shortly. On the Right Bank of Indus another drainage system out falling into the Sea is under construction. Further measures for overcoming the salinity and water logging problems are also being planned.

---

[1]Vice President, Water & Agriculture Division, National Engineering Services Pakistan (Pvt.) Limited, 1-C, Block-N, Model Town Extension, Lahore 54700 Pakistan Phone: 92-42-9231939 E-Mail: baq@nespak.com.pk and baq277@gmail.com
[2]General Manager, Water & Agriculture Division, National Engineering Services Pakistan (Pvt.) Limited, 1-C, Block-N, Model Town Extension, Lahore 54700 –Pakistan Phone: 92-42-9231955 E-Mail: gtcp@nexlinx.net.pk

INTRODUCTION

Agriculture plays pivotal role in the economy of Pakistan and is being practiced through the Indus basin Irrigation System which is one of the largest integrated irrigation networks in the world (Fig. 1).

Flat topography, lack of adequate natural drainage and its blockage by infrastructure development activities like highways, industries and housing, seepage from canals and deep percolation from fields, floods and rainfall are amongst the major factors contributing to water-logging and salinity hazards. Besides, canal irrigation supplies also cause addition of salt to the root zone. Irrigation with groundwater, the pumping of which is so far unregulated in Pakistan, further aggravates the situation by mobilizing salts from the groundwater aquifers.

The consequence of operating an interconnected irrigation system for decades, initially without drainage, and then interwoven with an inefficient, inadequate and discontinuous drainage system has been the cause of gradual rise of the water table and associated salinity in Pakistan.

EXISTING IRRIGATION AND DRAINAGE SYSTEM

Irrigation System

The Indus Basin Irrigation System (IBIS) has three major storage reservoirs, namely Tarbela and Chashma on River Indus, and Mangla on River Jhelum; 19 barrages (river diversion structures); 12 inter-river link canals; 45 independent irrigation canal commands, and 138,517 watercourses. The entire IBIS is shown schematically in Fig. 2. The salient features of the canals off-taking from various barrages/head works are given in Table-1.

Drainage System

Unlike the contiguous irrigation network, Pakistan’s drainage network is by sharp contrast not interconnected at all. Much of the drainage effluent is either retained within the Indus Basin Irrigation System (IBIS) or discharged into rivers, canals, lakes, evaporation ponds and the sea. Schematic layout of the existing drainage system is given in Fig. 3. Various natural drainage basins encompass a single canal command or a group of canals commands as shown in Fig. 4.

Gwadar

Figure 1 - Location Map

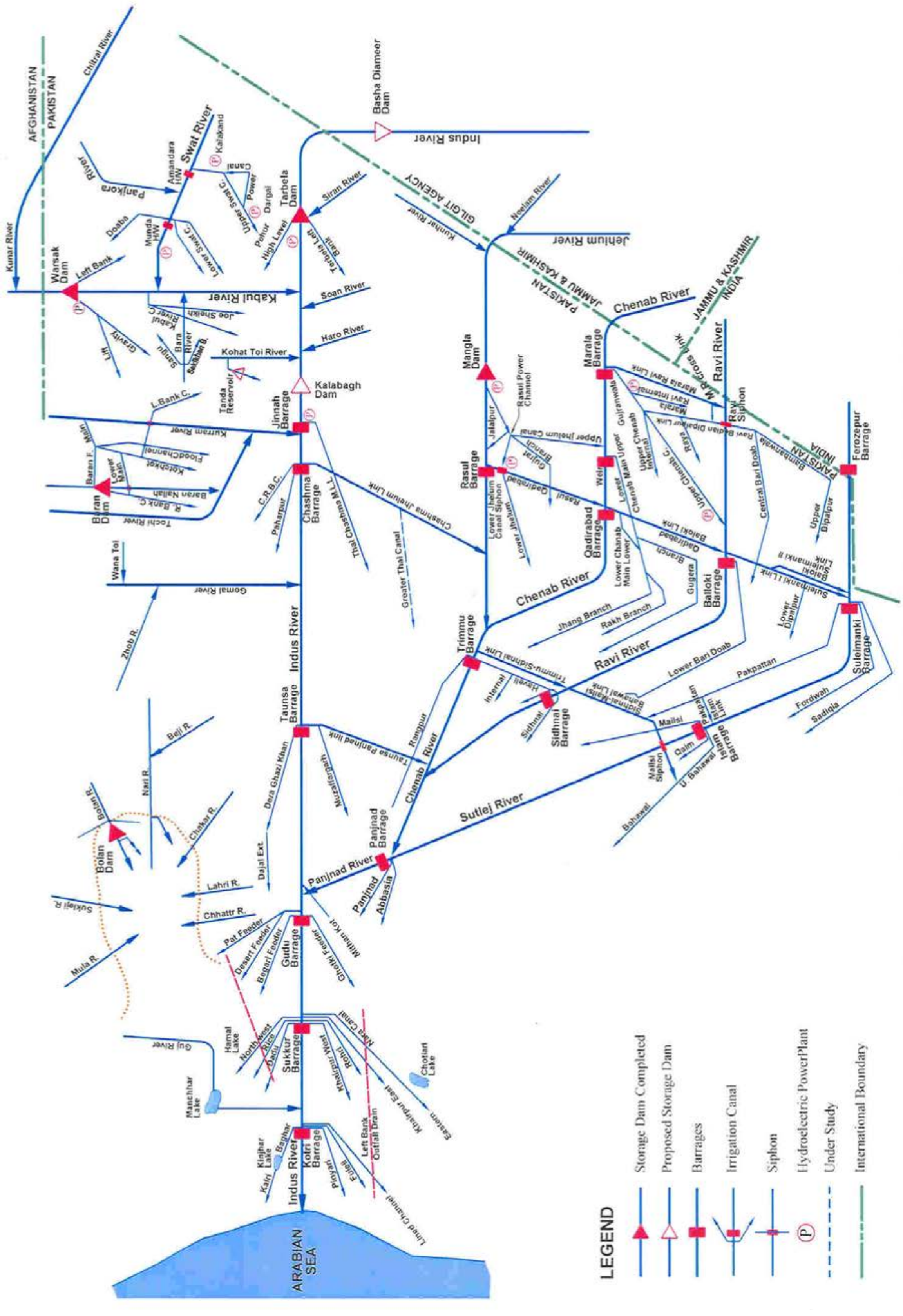


Figure 2 - SCHEMATIC DIAGRAM INDUS BASIN IRRIGATION SYSTEM

Table 1 - Salient Features of Indus Basin Irrigation System

Province	Barrage	River	Designed Capacity (m^3/sec)	Offtaking Canals			Area (1000 hectares)	
				Canals	Length * (km)	Discharge at Head (m^3/sec)	GCA	CCA
NWFP	Amandara	Swat	96	Upper Swat Canal	575	51	129	112
	Munda	Swat	55	Lower Swat Canal	276	23	59	54
	Warsak	Kabul	15,293	Warsak Left Bank Canal	160	1	5	4
				Warsak Right Bank Canal		13	51	44
				Kabul River Canal	138	13	37	31
	Tarbela	Indus		Pehur Canal				
	Chashma	Indus	28,321	CRBC	260	198	231	-
PUNJAB	Jinnah	Indus	26,905	Thal Canal	3233	212	941	651
	Chashma	Indus	28,321	Chashma Jhelum Link	1227	615	-	-
	Taunsa	Indus	21,240	Taunsa Punjnad Link	61	340	-	-
				Muzaffargarh Canal	1606	252	324	289
				D.G. Khan Canal	1706	235	318	283
	Rasul	Jhelum	24,073	Rasul Qadirabad Link	47	538	-	-
				Lower Jhelum Canal	2389	150	701	607
				Upper Jhelum Canal		54	282	219
	Marala	Chenab	31,153	Marala Ravi Link	101	623	72	43
				Upper Chanab Canal	2045	470	572	422
	Khanki	Chenab	29,737	Lower Chenab Canal	4552	331	856	674
				BRBD Link				
	Qadirabad	Chenab	25,489	Qadirabad Balloki Link	137	623	-	-
	Trimmu	Chenab	18,408	Trimmu Sidhnai Link	71	31	-	-
				Haveli Link	67	147	66	64
				Rangpur Canal	798	77	151	140
	Balloki	Ravi	6,372	Balloki Sulemanki Link		623	-	-
				Lower Bari Doab Canal	2321	255	769	617
	Sidhnai (New)	Ravi	4,730	Sidhanai Mailsi Link	100	286	424	397
				Mailsi Bahawal Link	16	110	-	-
				Sidhanai Canal	47	127	358	322
	Sulemanki	Sutlej	9,912	Eastern Sadiqia Canal	1377	164	46	381
				Fordwah Canal	772	96	191	173
				Upper Pakpattan Canal	1743	147	465	430
	Islam	Sutlej	10,988	U&L Bahawal Canal	1031	153	294	231
				Qaim Canal	11	14	-	-
	Punjnad	Punjnad	19,824	Punjnad Canal	2502	295	626	540
				Abbasia Canal	257	37	53	44
SINDH	Guddu	Indus	25,489	Ghotki Canal	1373	241	389	338
				Begari Feeder	1392	439	438	389
	Sukkur	Indus	42,481	Eastern Nara Canal	2554	379	977	928
				Khairpur East Canal	701	76	231	153
				Rohri Canal	3441	317	1154	1053
				Khairpur West Canal	1550	54	172	130
				North West Canal (partly)	1475	144	511	391
				Rice Canal	947	289	240	210
				Dadu Canal	964	91	255	223
	Kotri	Indus	25,489	Lined Channel	713	116	236	197
				Fuleli Canal	1114	391	409	376
				Pinyari Canal	1232	408	385	318
				Kalri Beghar Canal	1028	255	279	244
BALOCHISTAN	Guddu	Indus		Desert Pat Feeder	688	365	168	155
	Sukkur	Indus		North West Canal (Kirthar) partly	1475	144	511	391

* Given lengths are aggregate lengths of the canal systems including main canal, branches distributaries and minors.

Source: Main Report of Revised Action Programme for Irrigated Agriculture (1979), Master Planning and Review Division, WAPDA, Lahore.

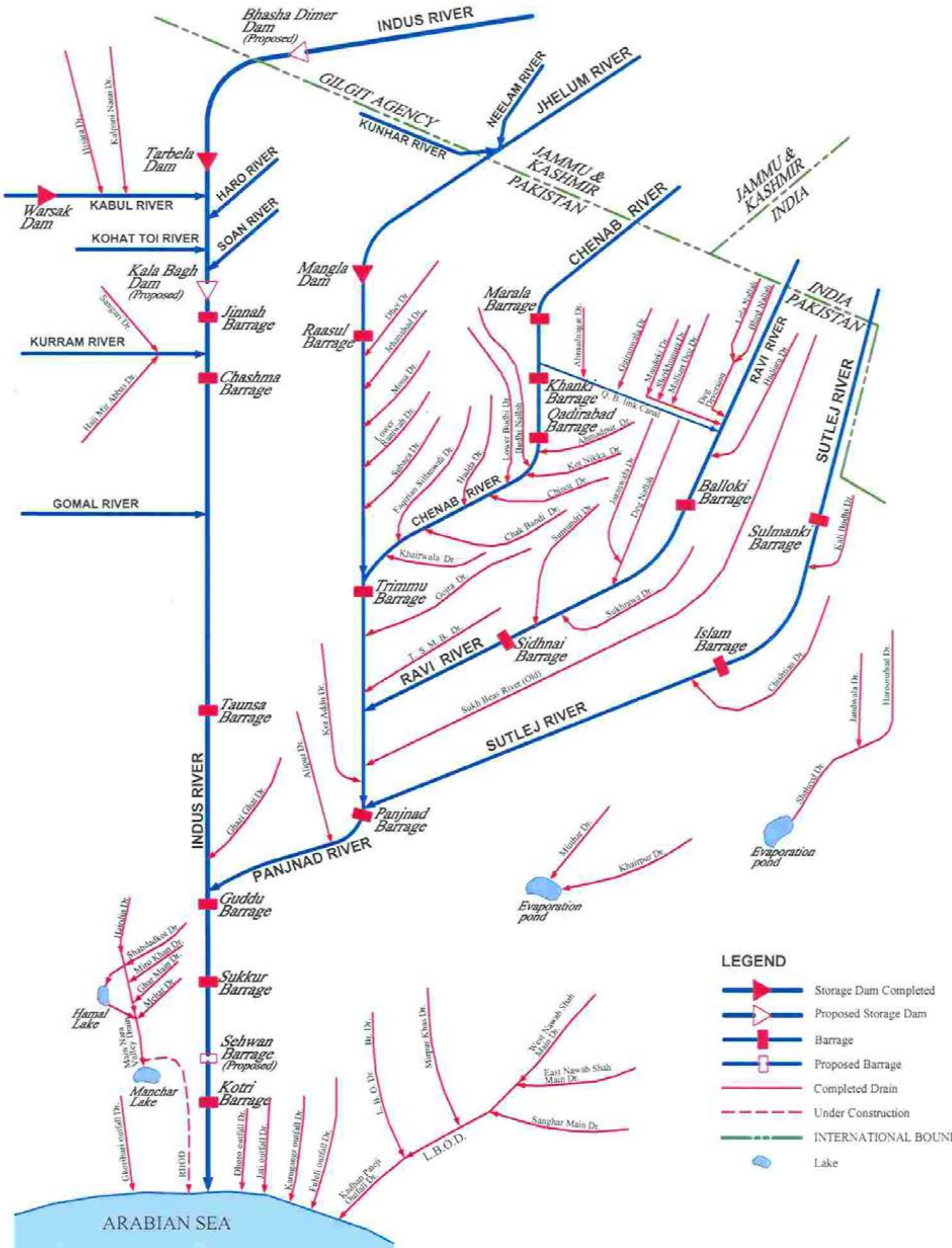
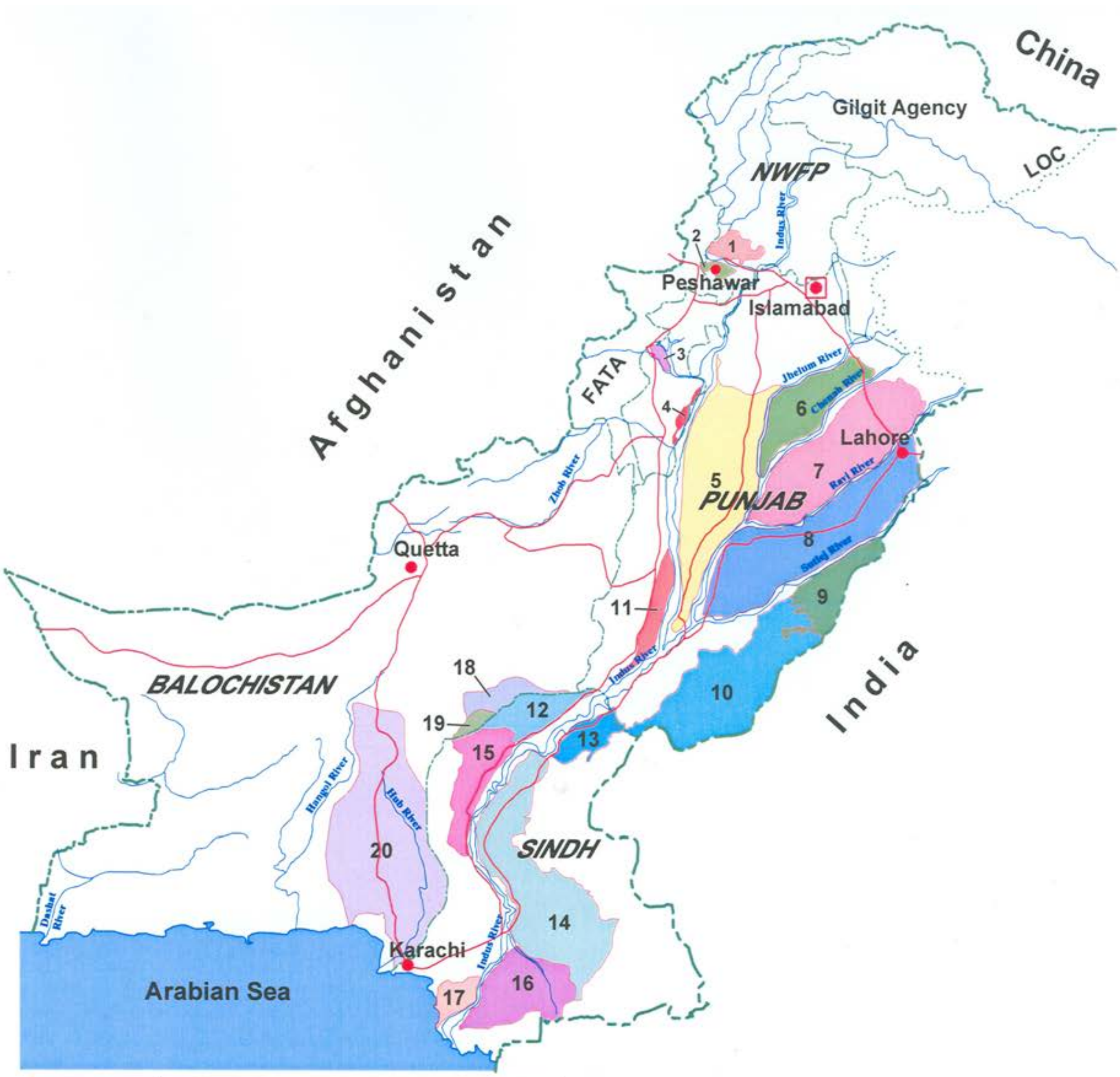


Figure 3 - SCHEMATIC DIAGRAM INDUS BASIN DRAINAGE SYSTEM



Province		Drainage Basin
NWFP	1	Swat Drainage System
	2	Kabul Drainage Basin
	3	Baran Drainage Basin
	4	Chashma Right Bank Drainage Basin
PUNJAB	5	Thal Doab Drainage Basin
	6	Chaj Doab Drainage Basin
	7	Rechna Doab Drainage Basin
	8	Bari Doab Drainage Basin
	9	Sutlej Left Bank (Fordwah) Drainage Basin
	10	Punjnad Left Bank Drainage Basin
	11	Indus Right Bank (D.G. Khan) Drainage Basin
SINDH	12	Guddu Left Bank Drainage Basin
	13	Guddu Right Bank (Sindh) Drainage Basin
	14	Sukkur Left Bank Drainage Basin
	15	Sukkur Right Bank (Sindh) Drainage Basin
	16	Kotri Left Bank Drainage Basin
	17	Kotri Right Bank Drainage Basin
BALOCHISTAN	18	Guddu Right Bank (Balochistan)
	19	Sukkur Right Bank (Balochistan) Drainage Basin
	20	Khuzdar and Lasbella Drainage Sub Projects

Figure 4 - Drainage Basins of Pakistan

Salient features of various drainage basins are given in Table 2. The existing drainage schemes have however not been developed on the basis of the basin approach. Instead these have been planned piecemeal over time addressing only local problem on need basis. The localized drainage solutions, which have so far been applied to the problem, have always lagged behind the rising tide of water logging and salinity and were never integrated with the overall water resources management systems.

Since 1960, Pakistan has been implementing an extensive program of Salinity Control and Reclamation Projects (SCARPs). Water and Power Development Authority (WAPDA) of Pakistan, has completed 63 (SCARPs) so far. The implementation status of various drainage projects is summarized in Table 3. Out of a total irrigated area of 16.7 Mha, 7.9 Mha area has already been provided with drainage facilities and further extension of such facilities is required to improve the remaining water-logged area.

EXTENT OF WATER LOGGING AND SALINITY

Depth to Water Table

Ground water table in the Indus Basin canal commands shows an annual cycle of rise and fall. The water table is measured twice a year during pre-monsoon (April/June) and post-monsoon (October) periods. It is at the lowest prior to the monsoon and rises to the highest point in October, due to recharge from irrigation and monsoon rains. High water table conditions after the monsoon are transitional and interfere slightly with the cultivation of winter crops. However, the aquifer levels in April/June truly represent the water-table conditions as they persist for a major part of the year and are used as the index of water logging. The area under depth to water table (0-1.5 m) during pre-monsoon is considered waterlogged/disastrous area. The province-wise pre-monsoon disastrous area for the period from 1978 to 2002 is shown in Table 4, which indicates that the disaster area has decreased slightly at the country level. Maximum extent of water-logged area occurred in 1999 due to heavy rains and abnormal floods in 1998 while the minimum was in 2001 due to drought conditions and increased pumping by private tube-wells.

Comparison of province-wise data shows that the disaster area remained almost constant in NWFP, increased in Sindh and Balochistan but there has been an overall decrease in the Punjab province. This decrease was mainly due to rapid growth of private tube wells in the province.

Surface Soil Salinity/Sodicity

In early stages of irrigation development, the needed salinity balance in the root zone was achieved without effort due to deep percolation of excess irrigation water, which carried the salts out of the root zone down to the water table. However, as the development extended with time, the water table containing these salts, rose to the level of the root zone. In large areas with extremely shallow water table, evaporation caused the salts to be left on the soil surface, which adversely affected crop production.

Table 2 - Drainage Basins and Canal Commands of the Indus Basin

Province		Drainage Basin	Canal Command
NWFP	1	Swat Drainage System	Upper Swat Canal Lower Swat Canal Pehur Canal
	2	Kabul Drainage Basin	Warsak Left Bank Canal Warsak Right Bank Canal Kabul River Canal
	3	Baran Drainage Basin	Marvat Canal
	4	Chashma Right Bank Drainage Basin	CRBC
PUNJAB	5	Thal Doab Drainage Basin	Rangpur Canal Chashma-Jhelum Link Canal Muzaffargarh Canal Thal Canal Taunsa-Punjnad Link Canal Greater Thal Canal (Under Construction)
	6	Chaj Doab Drainage Basin	Upper Jhelum Canal Rasul-Qadirabad Link Canal Lower Jhelum Canal
	7	Rechna Doab Drainage Basin	Upper Chenab Canal M.R. Link Raya Branch Canal Lower Chenab Canal Haveli Canal
	8	Bari Doab Drainage Basin	CBDC (Ravi Syphon) Upper Depalpur Canal Balloki-Sulemanki Link Canal Lower Depalpur Canal LBDC Pakpattan Canal Sidhnai-Mailsi Bhawal Link Canal Sidhnai Canal Mailsi Canal
	9	Sutlej Left Bank (Fordwah) Drainage Basin	Fordwah Canal Eastern Sdiqia Canal
	10	Punjnad Left Bank Drainage Basin	Bahawal Canal Qaim Canal Desert Branch Punjnad Canal Abbasia Canal
	11	Indus Right Bank (D.G. Khan) Drainage Basin	DG Khan Canal Dajal Canal Kachhi Canal (Under Construction)
SINDH	12	Guddu Left Bank Drainage Basin	Ghotki Feeder Rainee Canal (Under Construction)
	13	Guddu Right Bank (Sindh) Drainage Basin	Desert Feeder Begari Sindh Feeder
	14	Sukkur Left Bank Drainage Basin	East Nara Canal Khairpur East Canal Khairpur West Canal Rohri Canal
	15	Sukkur Right Bank (Sindh) Drainage Basin	Rice Canal Dadu Canal, North West Canal (Kirthar)
	16	Kotri Left Bank Drainage Basin	Lined Channel Fulelli Canal Pinyari Canal
	17	Kotri Right Bank Drainage Basin	Kalri Beghar Canal
BALOCHISTAN	18	Guddu Right Bank (Balochistan)	Pat Feeder Canal
	19	Sukkur Right Bank (Balochistan) Drainage Basin	North West (Kirthar) Canal
	20	Khuzdar and Lasbella Drainage Sub Projects	Flood Irrigation Schemes/Lasbella Canal

Source: International Waterlogging & Salinity Research Institute (IWASRI), WAPDA, Lahore.

Table 3 - Existing Drainage Facilities

(GCA in 000'ha)

Province	Drainage Basin	Sub Surface Drainage						Surface Drainage			Total
		Tubewell			Tile						
		FGW	SGW	No. of TWs	FGW	SGW	Length (Km)	FGW	SGW	Length (Km)	
NWFP	Swat	-	-		169	34		-	-		203
	Kabul	55	-		-	-		-	-		55
	Baran	31	5		-	-		-	-		36
	Chashma Right Bank	-	-		64	-		-	-		64
	TOTAL	**86**	**5**	**491**	**232**	**34**	**7,757**	**-**	**-**	**971**	**358**
PUNJAB	Thal Doab	503	89		-	42		-	9		644
	Chaj Doab	867	147		-	-		2	-		1,016
	Rechna Doab	800	420		12	40		142	87		1,501
	Bari Doab	71	8		-	-		247	82		408
	Sutlej Left Bank	28	48		-	-		5	246		327
	Punjnad Left Bank	510	168		-	-		-	-		678
	Indus Right Bank (Tounsa)	-	-		-	-			135		135
	TOTAL	**2,780**	**881**	**10,321**	**12**	**83**	**2,810**	**396**	**558**	**3,884**	**4,710**
SINDH	Guddu Right Bank	12	-		-	-		-	-		12
	Guddu Left Bank	178	-		-	-		-	-		178
	Sukkur Right Bank	66	-		-	-		-	420		486
	Sukkur Left Bank	631	87		-	18		-	577		1,314
	Kotri Right Bank	-	-		-	-		-	188		188
	Kotri Left Bank	-	-		-	-		-	546		546
	TOTAL	**887**	**87**	**6,138**	**-**	**18**	**2,046**	**-**	**1,731**	**9,186**	**2,724**
BALOCHISTAN	Guddu Right Bank	-	-		-	-		-	72		72
	Sukkur Right Bank	-	-		-	-		-	-		-
	Khuzdar-Lasbela	Area outside of the Indus Basin									
	TOTAL	-	-	-	-	-	-	-	**72**	-	**72**
PAKISTAN	**TOTAL**	**3,754**	**973**	**16,950**	**244**	**135**	**12,614**	**252**	**2,187**	**14,041**	**7,864**

Source: Monthly Progress Reports, Water Wing, WAPDA, (Upto June 2004) Planning & Design Division (Water), WAPDA, Lahore

Table 4 - Severely Waterlogged Area (0-1.5 m) April - June

(000'ha)

Year	Punjab	Sindh/ Balochistan	NWFP	Pakistan
1978	847	1074	30	1951
1979	1219	1234	31	2484
1980	890	1191	24	2105
1981	957	1079	43	2080
1982	1133	1040	37	2210
1983	1059	1107	52	2218
1984	787	1201	51	2040
1985	493	1271	39	1803
1986	767	1323	38	2129
1987	962	1130	42	2134
1988	540	898	57	1495
1989	648	1700	45	2393
1990	710	1442	49	2201
1991	765	1323	51	2139
1992	637	2364	47	3047
1993	663	2021	43	2727
1994	589	1372	39	2000
1995	489	1543	37	2069
1996	441	1276	36	1753
1997	620	2317	32	2969
1998	679	1834	30	2543
1999	619	2477	32	3128
2000	227	285	32	544
2001	109	508	30	647
2002	101	1162	29	1292

The first country-wide soil salinity survey was conducted in 1953-54 under the Colombo Plan assistance. The second survey was conducted by WAPDA during 1977-79 covering 16.7 Mha under which both surface and profile salinity were established through chemical analysis of the soil. The latest salinity/sodicity survey was completed in 2003. Overall countrywide and province/basin-wise extent of surface salinity based on the 2003 survey is given in Table 5.

Comparison with the past surveys indicates that the salt free lands increased from 56% in the early 1960s to 72% in 1977-79 and 73% in 2001-2003. The extent of lands affected by surface salinity also decreased from 42% in early 60's to 25% in 1977-79 and to 21% in 2001-2003.

Profile Salinity/Sodicity

Profile salinity/sodicity within 1.5 m depth was surveyed in Punjab in 1953-65 and in North West Frontier Province (NWFP) in 1971. Later on, countrywide profile salinity/sodicity survey was conducted by Planning Division, of WAPDA in 1977-79. Country/province-wise profile salinity/sodicity status is given in Table 6. Comparison of province-wise profile salinity/sodicity data given in Table 6 shows that profile salinity decreased with time as the salt free profiles increased from 55% in 1962-65 to 61% in 1977-79 and remained unchanged till the latest survey of 2001-03. Saline profiles increased from 6% in 1962-65 to 11% in 1977-79 and 22% in 2001-2003 respectively. However, non-saline-sodic profiles decreased to 3% in 1977-79 but increased again to 8% in 2001-2003.

The reduction in salinity (surface and profile) is primarily due to increased irrigation water application, better water management, increased cropping intensity and measures taken by the Government of Pakistan to reclaim the waterlogged and salt affected lands.

WATER AND SALT BALANCE

Water Balance

There are three most common types of water reservoirs in a basin or a sub-basin, namely surface water, unsaturated (root) zone and groundwater aquifer. Figure 5 illustrates water balance factors in a vertical section with respect to different reservoirs. The mathematical equations for water balance of these reservoirs are as follows.

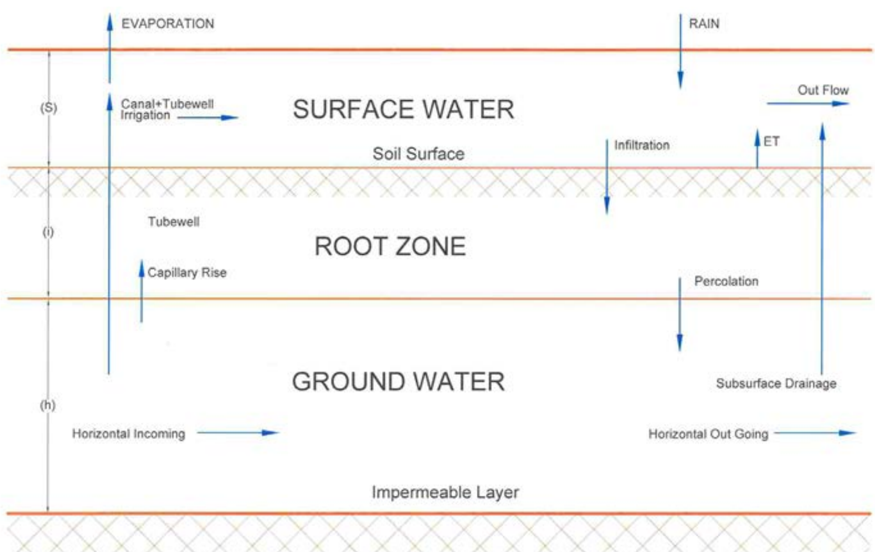


Figure 5 - Water Balance Factors in a Vertical Section of Land with Different Reservoir

The water balance for surface water can be expressed as:

Table 5 - Surface Salinity Status of the Indus Basin

(000,ha)

Province	Survey Period	Area Surveyed	Salt Free (S1)		Slightly Saline (S2)		Moderately Saline (S3)		Strongly Saline (S4)		Misc. Land Type	
			Area	%	Area	%	Area	%	Area	%	Area	%
NWFP	1971-75	614	458	75	63	10	21	3	14	2	58	10
	1977-79	614	480	78	50	8	14	2	9	2	61	10
	2001-03	745	642	86	13	2	11	2	3	*	76	10
PUNJAB	1953-65	10165	7287	72	1586	15	476	5	613	6	202	2
	1977.79	10165	8521	84	712	7	435	4	299	3	198	2
	2001-03	10119	8877	88	354	3	153	2	141	1	594	6
SINDH	1953-54	5579	1445	26	1565	28	962	17	1521	27	87	2
	1977-79	5579	2795	50	1038	19	578	10	999	18	168	3
	2001-02	5579	2557	46	1337	24	441	8	907	17	265	5
BALOCHISTAN	1953-54	353	245	69	53	15	25	7	30	9	0	*
	1977-79	353	261	74	60	17	16	5	14	4	2	*
	2001-02	353	234	67	53	15	33	9	24	7	8	2
PAKISTAN	1953-54	16711	9434	56	3267	20	1485	9	2178	13	347	2
	1977-79	16711	12058	72	1861	11	1042	6	1321	8	429	3
	2001-03	16797	12310	73	1757	10	637	4	1149	7	944	6

* Less than 1%

Source:
1) Soil Salinity and Watetable Survey Directorate , Survey and Research (S&R) Organization, Planning Division, WAPDA Lahore, 1981
2) Survey and Research Directorate, Scarp Monitoring Organization, WAPDA Lahore, 2001-2003.

Surface Salinity Definitions

Description	Class	ECe (dS/m)
Surface Salinity		
Non saline	S1	< 4
Slightly saline	S2	4-8
Moderately saline	S3	8-15
Highly saline	S4	> 15

Table 6 - Soil Profile Salinity/Sodicity Status Upto 1.5 m Depth in the Indus Basin

Province	Survey Period	Total Profiles (No)	Normal (NS-NS)		Saline (S)		Saline Sodic (S-S)		Non-Saline Sodic (NS-S)		Miscell-aneous	
			Area	%	Area	%	Area	%	Area	%	Area	%
NWFP	1971-75	314	86	27	156	50	71	23	1	*	-	-
	1977-79	1958	1553	79	216	11	138	7	28	2	23	1
	2001-03	1283	1070	83	118	9	71	6	23	2	1	*
PUNJAB	1962-65	23662	13023	55	1380	6	6376	27	2718	11	165	1
	1977-79	39963	29334	73	2803	7	5757	14	1813	5	256	1
	2001-03	17294	11718	68	955	6	2825	16	1796	10	-	-
SINDH	1977-79	20543	7918	38	3430	17	8677	42	373	2	145	1
	2001-03	5978	2151	36	1032	17	2606	44	188	3	1	-
BALOCHISTAN	1977-79	1402	497	35	365	26	528	38	12	1	-	-
	2001-03	205	80	39	41	20	74	36	10	5	-	-
PAKISTAN	1962-65	23976	13109	55	1536	6	6447	27	2719	11	165	1
	1977-79	63866	39302	61	6814	11	15100	24	2226	3	424	1
	2001-03	24760	15019	61	2446	9	5576	22	2017	8	2	*

* Less than 1%

Source: 1) Soil Salinity and Watertable Survey Directorate, Survey and Research Organization Planning Division, WAPDA, Lahore 1981

2) Survey and Research Directorate Scarp Monitoring Organization, WAPDA, Lahore 2001-03

Soil Profile Salinity Definitions

Description	Class	ECe(dS/m)	SAR
Non saline-Nonsodic	NS-NS	< 4	< 13
Saline Nonsodic	S-NS	> 4	< 13
Saline – Sodic	SS	> 4	> 13
Nonsaline – Sodic	NS-S	< 4	> 13

Rivers and Irrigation Canals + Rainfall + Tube well Pumping = Infiltration + Outflows + Evaporation + Change in Surface Storage ($\triangle$s).

The water balance for the root zone can be expressed as:

Infiltration + Capillary Rise = Evapo-transpiration + Percolation + Change in Soil Moisture ($\triangle$i).

The water balance for the groundwater zone can be expressed as:

Percolation + Horizontal Incoming Groundwater = Capillary Rise + Tube well Pumping + Subsurface Drainage + Horizontal Outgoing Groundwater + Change in Storage ($\triangle$h).

On the basis of water balance, it is possible to determine salt balance for the above mentioned reservoirs.

The components of groundwater recharge are summarized in Table 7. Total recharge to the aquifers of the Indus Basin on broad based calculations has been estimated as 83 billion cubic meter (BCM) per year, out of which 58 BCM is through canal irrigation system, 9 BCM is from rainfall and 17 BCM results from recirculation through tube well irrigation.

Table 7 – Groundwater Recharge of the Indus Basin

Location	**At Head (BCM)**	**Infiltration**		**Recharge to Aquifer**	
		%	**BCM**	**%**	**BCM**
1. Canals Diversions					
Canals	128.28	15	19.24	75	14.43
Distributaries	109.04	8	8.72	75	6.54
Watercourses	100.32	30	30.10	60	18.06
Fields	70.22	30	21.07	90	18.96
Crops	49.15	-	-	-	-
Sub-Total (1)	-	-	79.13	-	57.99
2. Tubewells					
Watercourses	55.51	10	5.55	60	3.33
Fields	49.96	30	14.99	90	13.49
Crops	34.97	-	-		-
Sub-Total (2)	11.10		20.41		16.82
3. Rainfall: Average Rainfall of 0.2 m over area of 16.6 Mha.					
Rainfall Recharge(3)	34.54	50	17.27	50	8.63
Total Recharge	29.97	-	14.93	-	83.45

Source: International Water-logging and Salinity Research Institute, WAPDA, Lahore

Salt Balance

As salts are not removed with evaporation from soil and water, the salt balance of surface water can be calculated from the following equation:

(Irrigation – Infiltration) x Salt Contents + Rainfall x Salt Contents =
Drain Discharge x Salt Contents + Change in Salt Storage.

The salt balance equation for the root zone can be expressed as:

Infiltration x Salt contents + Capillary Rise x Salt Content -
Deep Percolation x Salt Contents = Change in Salt Storage

Salt balance equation for groundwater aquifer is as follows:

Deep Percolation x Salt Contents + Groundwater Inflow x Salt Contents –
Subsurface Drainage x Salt Contents + Groundwater Outflow x
Salt Contents = Change in Salt Quantity in Groundwater

The indicative salt balance of the Indus Basin determined on the basis of the above equations is presented in Table 8. For the purpose of these calculations, the data for volume of water are taken from water sector reports. Besides, as water quality has a wide variation, average values have been used for calculation of salt balance. The data presented in Table 8 indicate that there is addition of salts at the rate of 11.12 tonne per year to the groundwater aquifer.

DRAINAGE DISPOSAL

Drainage scheme so far completed, are based on tube wells, tile drains & surface drains. The mode of disposal is re-use of water in fresh groundwater areas, disposal into rivers, lakes, evaporation pond and directly into the sea. Basin-wise disposal arrangements are given in Table 9.

In Upper Indus Basin, (mostly Punjab), drainage effluent in FGW areas is being used to supplement irrigation supplies directly or after mixing with fresh water by disposal into canals, distributaries and minors. Thus the salts brought up from the aquifer remain in recirculation. In order to maintain the water table below root zone, drainage effluent from SGW areas is being disposed of into drains from where it is carried to the rivers. Some part of salt load reaches the irrigated area within Punjab through canal diversions while some part is passing downstream through Panjnad as part of flood flows.

The drainage water from the areas marginal to saline groundwater is being disposed of into rivers except for the area on the left bank of Sutlej river, from where SCARP-VI and Fordwah-Eastern Sadiqia (South) Phase-1 projects lead the saline drainage effluent into evaporation ponds located among the sand dunes.

Table 8 - Indicative Salt Balance of the Indus Basin Upstream Kotri

Doab/Basin	Annual Volume (BCM)	Quality (ppm)	Salts (Tonne)
SURFACE WATER			
Inflows			
Rim stations inflows	172.69	150	28.15
Outflows			
Canal diversions upstream Kotri	115.09	170	21.26
Kotri right command	3.58	270	1.08
Kotri left command	9.74	270	2.85
Indus flow downstream Kotri	44.41	200	9.65
Sub-Total			**34.84**
Balance			**-6.69**
ROOTZONE/UNSATURATED ZONE			
Inflows			
Infiltration canal supplies	115.09	170	20.73
Infiltration tubewells	55.51	800	48.23
Rainfall	16.04	0	0.00
Capillary rise	5.80	1,000	6.30
Sub-Total			**75.26**
Outflows			
Recharge from canal supplies	52.05	800	45.18
Recharge from tubewell supplies	16.78	1,300	23.62
Recharge from rainfall	8.02	800	6.99
Sub-Total			**75.79**
Balance			**-0.53**
GROUNDWATER			
Inflows			
Recharge from canal supplies	52.05	800	45.18
Recharge from tubewell supplies	16.78	1,300	23.62
Recharge from rainfall	8.02	800	6.99
Sub-Total			**75.79**
Outflows			
Capillary rise	5.80	1,000	6.30
Irrigation tubewell discharge	55.51	800	48.23
Groundwater outflow LBOD	0.23	14,523	3.74
Groundwater outflow SCARP VI	0.23	25,098	6.40
Sub-Total			**64.67**
Balance			**11.12**

Table 9 - Drainage Disposal

Province	Drainage Basin	Type of Drainage						Disposal Option			
		Type of Drainage				Surface Drainage		Re-cycled	Into River	Into Evaporation Pond / Lake	Into Sea
		Tubewell		Tile							
		FGW	SGW	FGW	SGW	FGW	SGW				
NWFP	Swat	✓		✓		✓		✓	✓		
	Kabul	✓						✓			
	Baran	✓						✓	✓		
	Chashma Right Bank			✓				✓			
PUNJAB	Thal Doab	✓	✓		✓		✓	✓	✓		
	Chaj Doab	✓	✓			✓		✓	✓		
	Rechna Doab	✓	✓	✓	✓	✓	✓	✓	✓		
	Bari Doab	✓	✓			✓	✓	✓	✓		
	Sutlej Left Bank	✓	✓			✓	✓	✓	✓	✓	
	Punjnad Left Bank	✓	✓					✓		✓	
	Indus Right Bank (Tounsa)						✓		✓		
SINDH	Guddu Right Bank	✓						✓			
	Guddu Left Bank	✓						✓			
	Sukkur Right Bank	✓					✓			✓	
	Sukkur Left Bank	✓	✓		✓		✓	✓			✓
	Kotri Right Bank						✓				✓
	Kotri Left Bank						✓				✓
BALOCHIS-TAN	Guddu Right Bank						✓			✓	
	Sukkur Right Bank										
	Khuzdar-Lasbela										

Source: Monthly Progress Reports, Water Wing, WAPDA, (Upto June 2004) Planning & Design Division (Water), WAPDA.

In order to maintain the water table below root zone, drainage effluent from highly SGW areas is being disposed of into drains from where it is carried to the rivers. Some part of salt load reaches the irrigated area within Punjab through canal diversions while some part is passing downstream through Panjnad as part of flood flows.

In Lower Indus Plains (Sindh), tube well drainage was started in FGW in left bank and right bank command areas to control water-logging and salinity. The drainage effluent was mixed with canal supplies to facilitate easy disposal and supplement irrigation supplies. Hence, the issue of salt balance in FGW areas in Sindh is similar to FGW areas in Punjab. Under the LBOD Project, subsurface drainage facilities have been provided in saline ground water areas and surface drainage in rice areas simultaneously on the left bank of Indus. Disposal of saline effluent has been made simple by disposing it of into the sea through LBOD.

In the right bank command areas of Guddu and Sukkur barrages , the drainage effluent is being re-used for irrigation purposes in some areas, while in some parts surface drainage has been provided to facilitate evacuation of saline effluent and drainable surplus from rice areas into Hamal and Manchar lakes. Presently the Right Bank Outfall Drain (RBOD) is under construction, which will convey all the drainage water from the Indus right bank area into the Arabian Sea. Thus the issue of salt balance in the root zone and on regional basis will be adequately covered for both right bank and left bank irrigated areas in Sindh and Balochistan as RBOD will also cater for both the provinces.

The drainage water in NWFP is generally of useable quality, except in Baran Drainage Basin where about 50% of the area is underlain by marginal to hazardous quality of groundwater. The drainage effluent from tube-wells in fresh ground water areas is being re-used for irrigation that from the remaining areas is being discharged into rivers.

ENVIRONMENTAL IMPACTS

Water Logging of the Area

Water logged lands provides a good habitat for mosquitoes and other undesirable insects. Besides the salt affected lands have long been neglected for agricultural and operational interests and the wild vegetation growing thereon hosts various types of insects and pests which damage the crops in surrounding healthy crops. The marginal soils in wastelands also accommodate harmful species for creepers, rodents and other terrestrial population, which may pose environmental hazards for the surrounding areas and human life. The area where drainage has not been provided therefore presents severe environmental problems.

Salinity of Soil

In FGW areas, tube wells drainage effluent has always been used to supplement irrigation supplies for meeting crop water requirements. Even in SGW areas wherever there are pockets of fresh to marginal quality of water, it has been an accepted practice to use ground water for supporting agriculture as well as for lowering water table. The environmental impact of such practice is the continuous build up salinity in the aquifer below water table, while the root zone is kept relatively free of salinity build up. Latest evaluation of various projects has revealed an increasing trend of salinity in the aquifer on long term basis.

Evaporation Ponds

The adverse environmental impacts of the evaporation ponds of the SCARP-VI and Fordwah Eastern Sadiqia Project (FESSP) have been observed to outweigh the benefits of this local solution for the disposal of the saline effluent. The evaporation ponds have resulted in permanent loss of land and the data obtained from SCARP-VI and FESSP evaporation ponds has indicated that the quality of drainage effluent in the ponds has been deteriorating with the passage of time. Seepage towards the down slope agricultural lands and spray of salty dust on the peripheral lands in dry season are some of the serious environmental hazards being experienced in the above mentioned areas.

Damage to Wet Lands

Pakistan possesses a great variety of wetlands. Out of these, two major lakes, Manchhar and Hamal lakes are of prime national and international importance. These wetlands provide resting area and feeding grounds along the migration routes of birds. Drainage effluent from Indus right bank area to these lakes is causing significant environmental degradation of these lakes. As mentioned earlier, with the completion of the Right Bank Outfall Drain by the end of 2008, this environmental hazard will be taken care of.

Water Quality of Drains

The existing surface drains in various drainage basins dispose of the relatively saline groundwater drainage effluent mostly into the rivers where dilution takes place according to the assimilative capacity of the rivers. However, in addition to saline groundwater, municipal and industrial wastes are also being discharged into these drains, causing irreversible deterioration of the river waters, which are to irrigate the downstream areas. Water quality in some of the drains is given in Table 10, which represents a very dismal state of affairs. Province-wise drain water quality is summarized below:

Punjab:

(a) All the drains carrying drainage effluent have highly saline and sodic water having high values of EC, RSC and SAR.
(b) All drains have values of COD and BOD higher than the permissible limits.
(c) Some heavy metals and toxic elements are higher than the permissible limits.
(d) Pesticides/insecticides and other agro-chemicals are higher than the permissible limits in all the drains.

Table 10 - Drains Water Quality

Sr. No.	Location	Drainage Basin	EC (us/cm)	RSC m.eq/l	SAR	OXYGEN DEMAND COD (mg/l)	OXYGEN DEMAND BOD (mg/l)	HEAVY METALS CN (ppm)	Cd (ppm)	Cu (ppm)	Cr (ppm)	Pb (ppm)	Ni (ppm)	Zn (ppm)	As (ppm)
1	Dallas Drain	Kabul	720	0.50	2.17	137.20	68.55	-	0.05	0.08	0.01	-	0.01	0.03	0.11
2	Budni Nullah	Kabul	740	0.30	1.77	133.28	67.73	-	0.04	0.06	0.01	-	0.01	0.02	0.15
3	Murdara Drain	Kabul	920	3.20	3.57	176.40	94.27	-	0.05	0.03	0.01	-	0.02	0.04	0.08
4	Kalpani Nullah	Swat	750	1.80	2.44	207.76	104.59	-	0.03	0.08	0.01	-	0.02	0.04	0.30
5	Kalpani Nullah	Swat	800	1.90	2.67	168.36	82.31	-	0.08	0.06	0.01	-	0.01	0.02	0.20
6	Hisara Drain	Swat	810	3.00	3.90	86.24	54.86	-	0.06	0.10	0.01	-	0.01	0.02	0.18
7	Raniwah Drain	Chaj	8000	0.00	28.39	78.00	15.00	0.091	0.001	ND	2.709	0.668	1.919	0.0303	-
8	Chak Bandi Drain	Rechna	5000	14.70	26.40	361.00	235.00	0.067	0.01	ND	1.362	0.428	1.37	0.0741	-
9	Summandri Drain	Rechna	6000	17.30	27.93	352.00	79.00	0.143	0.013	ND	1.223	0.813	1.389	0.0346	-
10	Jaranwala Drain	Rechna	8000	0.00	23.25	754.00	161.00	0.487	0.005	ND	3.065	0.731	3.089	0.0884	-
11	Huddiara Drain	Bari	1620	7.00	8.32	315.00	115.00	0.977	0.002	ND	0.939	0.490	0.109	0.0369	-
WHO/NEQS Permissible Limits			**1500**	**2.50**	**10.00**	**150.00**	**80.00**	**2.00**	**0.10**	**1.0**	**1.0**	**0.50**	**1.0**	**5.0**	**0.50**

* Samples taken during November and December, 2001

** Source: Scarp Monitoring Organization Report submitted to National Drainage Programme Office.

Water Quality Definitions

Description	EC 10^6 (micro-mhos/cm)	EC (dS/m)	SAR	RSC
Fresh (usable)	< 1500	< 1.5	< 10	< 2.5
Marginal	1500-3000	1.5-3	10-18	2.5-5
Hazardous	> 3000	> 3	> 18	> 5

NWFP:

a) The drainage effluent carried by the drains is generally useable.
b) COD and BOD values are higher than the permissible limits.
c) Heavy metals and toxic elements are generally within permissible limits while copper and nickel are a little bit higher during some sampling periods.
d) All the drains show values for insecticides/pesticides higher than the permissible limits.

Balochistan:

a) Majority of drains had highly saline water due to higher EC.
b) RSC was generally zero.
c) COD values were higher than permissible limits while BOD values were within permissible limits.

Sindh:

a) Most of the drains contain highly saline water with high EC values.
b) RSC was mostly nil.
c) SAR is generally high.

Disposal of Industrial Effluent

Despite the development of National Environmental Quality Standards (NEQS)), very few industries in Pakistan have proper effluent treatment facilities. Because of high loads of organic and toxic materials, industrial effluent is a major source of water pollution.

The highly polluting industrial areas of Karachi include the Sindh Industrial Trading Estate (SITE), Landhi Industrial Area (LIA), Korangi Industrial Area (KIA) and a cluster of heavy industries around Port Qasim. Untreated effluents containing toxic wastes are discharged from these areas via the Malir and Lyari Rivers and Gizri Creek into the sea. Heavy metals such as lead, chromium and copper have been detected in Karachi's drinking water supplies, in subsoil water and in groundwater near to the Korangi industrial area of Karachi. The total pollution load of the tanneries in the Korangi area has been estimated at 29.5 tonne/day of BOD, 39.4 tonne/day of suspended solids, 22.6 tonne/day of oil and grease, and 2.56 tonnes/day of chromium.

In Punjab, a wide range of industries has grown up in the urban centers of Lahore. Faisaslabad, Multan and Sialkot. A large industrial complex a Kala Shah Kaku, a few kilometers north of Lahore, contains a variety of industries which discharge 15 mgd of untreated effluent via Deg Nullah into the River Ravi. The industrial complex on Lahore-Sheikhupura road and the Lahore Township Industrial Estate (LTIE) contribute effluent flows of 11 mgd and 7 mgd respectively to the Ravi. Untreated wastewater from industries in Multan and Faisalabad find their way into the Chenab River. The major industries of Punjab have been estimated to generate around 2,360 tonne/day of BOD. Besides, one of the most well-known and widely quoted cases of industrial pollution is that of the Kasur town, where wastewater from tanneries has caused extensive groundwater pollution with chromium and other contaminants. Industrial waste water discharges from various districts of Punjab province are given in Table 11.

In NWFP, the Kabul River has long been a receptor of industrial and municipal effluents. Industrial estates in and around Peshawar discharge their untreated waste into the Bara River and onwards into the Kabul River. Industries near Nowshera discharge about 32 mgd of their effluent into the Kabul River via the Kalapani River.

Table 11 - Industrial Waste / Municipal Effluent Discharges of Punjab

District	Number of Units			Discharge (mgd)	Quality
	Industrial Units	Municipal Units	Total Units		
Faisalabad	115	8	123	158	Unfit
Lahore	138	15	153	2103	Unfit
Hafizabad	3	2	5	33	Unfit
Gujranwala	53	13	66	66	Unfit
Sialkot	37	2	39	47	Unfit
Kasur	22	1	23	41	Unfit
Sheikhupura	151	7	158	109	Unfit
Mandi Baha Uddin	8	3	11	27	Unfit
Gujrat	3	1	4	21	Unfit
Sargodha	11	15	26	55	Unfit
Jhang	5	4	9	8	Unfit
Khanewal	3	1	4	6	Unfit
Multan	7	2	9	134	Unfit
Lodhran	2	1	3	9	Unfit
Bahawalpur	3	1	4	5	Unfit
Bahawalnagar	2	1	3	4	Unfit
Rahim Yar Khan	4	1	5	6	Unfit
Dera Ghazi Khan	2	1	3	39	Unfit
Muzaffargarh	6	1	7	21	Unfit
Sahiwal	2	1	3	6	Unfit
Toba Tek Singh	2	1	3	2	Unfit

Disposal of Municipal/Domestic Effluent

Most of the large cities in Pakistan have no wastewater treatment facilities and municipal/ domestic sewage is discharged into natural water bodies. There is a widespread assumption that the receiving surface water have unlimited dilution and assimilation capacity. Sewage treatment plants have been built at Islamabad, Karachi and Hyderabad, but treatment is intermittent and partial. In Karachi, treatment capacity is available for only 53 mgd out of the 342 mgd of effluent produced. Lahore puts much of its untreated municipal sewage into the River Ravi, which is used for irrigation and domestic water supply further downstream. Kabul River receives urban and industrial effluents from Peshawar, Mardan and adjoining areas. In Quetta, municipal wastewater is conveyed to a watercourse from which it is pumped for vegetable irrigation. Without sewage treatment facilities, domestic/municipal effluent combined with industrial waste poses an ever-increasing threat to environment as well as human and animal health.

Water Quality of Rivers

Water quality of various rivers of Pakistan is given in Table 12. The discharge of untreated sewage and industrial waste effluent into drains and ultimately into rivers is the main cause of deterioration of the river water quality. This impact is more pronounced during the low flow period (October – April). The water quality of Ravi River, which suffers extreme shortage of water because its head waters are all used up in India, is most seriously affected due to disposal of untreated sewerage from Lahore and other towns and also due to discharge of industrial effluent from Kala Shah Kaku (near Lahore) industrial estate and other industries discharging through Deg Nullah into Ravi River.

From the data of Indus River water quality at Kotri Barrage from 1974 to 2002, presented in Table 13, it can be seen that the water salinity (TDS) ranged between 140 to 400 ppm except one value of 640 ppm in August, 1990. It can therefore be concluded that the quality of river water at this point is suitable for irrigation purpose. However, during low flow period in Indus river, water supply to Hyderabad city is supplemented from Manchhar Lake, which has been polluted over the years by inflows of Main Nara Valley Drain, carrying saline drainage from the Indus Right Bank area as well as industrial and domestic sewage to the lake.

Table 12 - River Water Quality

Sr. No.	Location	Upstream Drainage Basin	EC (µs/cm)	RSC meq/1	SAR	OXYGEN DEMAND		HEAVY METALS							
						COD (mg/l)	BOD (mg/l)	CN (ppm)	Cd (ppm)	Cu (ppm)	Cr (ppm)	Pb (ppm)	Ni (ppm)	Zn (ppm)	As (ppm)
1	Shah Alam River Upstream	Kabul	470.00	0.20	1.45	109.76	52.28	-	0.05	0.10	0.01	-	0.02	0.01	0.12
2	Shah Alam River Downstream	Kabul	670.00	0.05	2.01	156.80	86.59	-	0.04	0.07	0.01	-	0.02	0.02	0.13
3	Kabul River Upstream	Swat	520.00	0.00	1.46	148.96	75.45	-	0.03	0.05	0.01	-	0.02	0.03	0.09
4	Kabul River Downstream	Swat	530.00	0.60	2.16	207.76	96.00	-	0.03	0.04	0.01	-	0.01	0.02	0.10
5	Jhelum River Upstream	Chaj	320.00	0.00	1.10	27.00	9.00	0.07	ND	ND	0.732	0.222	0.562	0.0203	-
6	Jhelum River Downstream	Chaj	330.00	0.00	1.63	34.00	7.00	0.086	ND	ND	0.224	0.35	0.325	0.0396	-
13	Indus River at Chachran	Indus Right I	310	0.20	0.96	75.00	29.00	0.074	ND	ND	0.02	0.26	0.651	0.0769	-
WHO/NEQS Permissible Limits			1500	**2.50**	**10**	**150.00**	**80.00**	**2.00**	**0.10**	**1.00**	**1.00**	**0.50**	**1.00**	**5.00**	**5.00**

- Samples taken during November and December, 2001
- Source: Scarp Monitoring Organization Report submitted to National Drainage Programme Office.

Table 13 - Quality of Indus River Water at Kotri Barrage

(PPM)

Year	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1974	-	-	-	400	280	190	-	-	-	173	245	217
1975	252	252	295	368	263	168	151	182	210	224	252	252
1976	260	260	298	296	298	210	227	102	245	242	326	325
1977	326	304	403	397	298	263	183	182	224	224	226	228
1978	228	308	273	236	238	182	273	189	306	266	301	266
1979	228	245	242	273	182	193	140	165	186	139	193	182
1980	172	305	319	336	273	182	175	189	186	187	235	236
1981	247	277	350	347	248	168	158	209	195	199	221	239
1982	249	266	261	350	270	237	181	175	207	162	186	193
1983	193	221	298	-	-	-	-	-	-	-	-	-
1984	-	-	-	343	344	337	196	200	224	245	244	241
1985	224	280	302	280	374	228	183	179	173	168	208	232
1986	191	249	281	-	-	-	-	-	-	-	-	-
1990	-	-	490	210	-	-	150	640	200	170	190	240
2001	-	-		-	-	159**	-	169	-	-	177	-
2002	292*	196*	254**	195	191	-	-	176	188	188	193	188
Ave.	283.50	263.58	312.76	287.30	271.58	209.75	183.36	219.76	215.53	199.00	288.35	233.77
Max	326	308	490	400	374	337	273	640	306	266	326	325
Min	172	308	196	195	182	159	140	165	154	139	177	182

Source: Integrated Water Resources Management Programme for Pakistan – Surface Water Resources Study, IWASRI Internal Report No. 98/1 56-65
Pakistan Drainage Sector Environment Assessment Report – National Drainage Programme
* IEM Study – SMO (2002) unpublished data
** Indus and Louisberger Consultants, National Surface Drainage System Feasibility Report, September 2002.

Sea Water Intrusion

Sea water intrusion is a major problem in the coastal areas of Sindh and Balochistan. Indus River, LBOD and the natural streams falling into the Arabian Sea are influenced by tidal fluctuations. Studies indicate that tides and water currents increase the salinity in the out falling channels. In the Tidal Link system of LBOD, sea water intrusion is observed up to 28 km inside the Kadenji Pateji Outfall Drain (KPOD) and its effect is maximum during the period from April to August.

FUTURE STRATEGY

Although in general, the water-logging and salinity situation has gradually improved over the past few decades, especially in Punjab province, there are vast areas, especially in Sindh province, which need substantial remedial measures. As stated earlier, the factors that brought improvement in Punjab province include both the measures implemented by the government through SCARPs and those by the private sector through rapid growth of tube wells for supplementing irrigation water. An additional natural factor that has caused some improvement in the water-logging situation has been the drought in the recent years, which may in fact be a capricious element.

While the public and private sector interventions have brought about apparent improvement, these have been agents to some adverse effects as well. The main reason for this is adoption to localized drainage solutions instead of employing an integrated basin approach taking into account both the water resources management and drainage aspects and exercising properly regulated control over use of surface and ground waters. It has therefore been realized recently that a comprehensive approach needs to be developed in order to achieve long term balance among the various contributing factors. A general outline of this approach and is presented below.

Integrating Drainage and Water Management

The Indus Basin irrigation and drainage system have to be developed and managed in an integrated manner. Any activity at a point within the basin may affect either positively or negatively at another location within the same basin. The approach of shifting the problem from one place to another can no longer be acceptable.

In the Indus Plains excellent aquifer characteristics permit use of the good quality groundwater where it is drained, but in areas with saline groundwater, suitable means for removal and safe disposal of drainage water are urgently required. With the availability of good drainage infrastructure corresponding to the irrigation system as a whole, it will be possible to manage, both water-logging and salinity problems in an integrated manner.

The entire irrigated area of Indus basin has been divided in to twenty drainage basins as shown on Fig. 3. An integrated approach taking into account all the inter-related aspects of water management, use and regulation of ground water, various types of drainage measures, salinity management needs, re-cycling possibilities of drainage effluent, bio-saline alternatives and environmental management should be adopted within each basin as well as intra-basin, in such a manner that quantity of drainage effluent for ultimate disposal is reduced to the minimum and the final disposable effluent is of acceptable water quality with respect to the assimilation capacity of the receiving water body, in order to ensure minimum negative impact on downstream users.

Equitable Distribution of Irrigation Water

In most of irrigation canals head reach users are drawing more water than their share. As a result they have lesser dependency on groundwater and water table levels remain high in such reaches. Improved and equitable distribution of canal water through participatory management of irrigation system is therefore essential for control of water-logging in head reaches of canals. Projects based on the modern concepts and control measures for ensuring equitable distribution are already on the anvil.

Besides agriculturists, many other stakeholders are also disposing of undesirable effluents into the drainage systems. Therefore, industries and municipalities are also being involved now in drainage and water management aspects.

Reduction of Recharge from Irrigation System

Excessive seepage from the irrigation canals, distributaries and watercourses and deep percolation from the fields are the main causes of the widespread water-logging and salinity. Unequal distribution of water between the upper and lower reaches of the distribution system, water theft and over-irrigation are also visible causes of water-logging. A number of irrigation improvement programs have been launched recently for water saving, which include canal lining, watercourse lining and improvement, land leveling, improved scheduling and improved field water application by employing high efficiency irrigation systems like drip and sprinkler irrigation.

Government of Pakistan is now placing greater emphasis on lining of irrigation channels. In the three major ongoing projects i.e., Greater Thal, Rainee and Kachhi canal systems, a substantial part of irrigation systems is being provided with impervious lining which will not only help in controlling water-logging but will also save a significant amount of water. In addition, the Provincial Governments have started massive programs of lining of distributaries and minors. The National Program for Improvement of Water Courses is already being implemented on fast track in all the provinces, involving partial lining of 138,517 water courses in the entire country.

Replacement of Saline Drainage Tubewells

Saline tube wells for drainage have been bringing salts from deep aquifer to surface. The objective of lowering of water table can be achieved in a better way by piped drainage, which would generate lesser discharge effluent and the effluent will be of much better quality than the tube-wells and could be easily re-circulated for irrigation purposes. Replacement of saline drainage tube wells with piped drainage systems in water-logged areas is therefore recommended

Recycling of Drainage Effluent

The volume of drainage water requiring ultimate disposal can be reduced by reusing it progressively for more salt tolerant crops, trees and fodders. The drainage water applied to such crops would be reduced in volume through evapo-transpiration along with dissolved constituents such as salts, which is a much easier way to manage the drainage the drainage effluent in an environmentally safe manner. Thus volume reduction through reuse would substantially reduce the cost of disposal of the drainage effluent.

The initial good quality water can be used to grow high value crops, such as vegetables. Drainage water captured in the tile drainage system under these lands can be collected and pumped into a local distribution system for a salt-tolerant field crop, such as cotton.

Drainage from these fields could then become the water supply for salt-tolerant trees such as eucalyptus, which are capable of high transpiration rates and would thus reduce the drainable surplus substantially. Finally, drainage from the trees could be used on halophytes that grow in extremely saline conditions.

At that stage of the reuse process, the extremely concentrated drainage water must be disposed of into the sea.

Salinity Management

For the sustainability of irrigated agriculture, it is of permanent importance that a favorable salt balance is maintained in root zone of crops. Salt water balance needs to be assessed on a drainage basin or sub-basin level. More canal water in the fields needs to be applied to leach down the excessive salt. Farmers need to be educated about the water quality of their tube wells and the hazards resulting from continuous application if water quality is poor. Farmers should also be educated to retain rain water in their fields by discouraging its immediate discharge to surface drains, which will help in leaching of salts.

Developing Saline Agriculture/Bio-Saline Alternative

Saline agriculture is a good compliment to engineering and reclamation approaches to the problems of water-logging and salinity. It provides local solution to saline land and saline irrigation water on sustained basis under controlled and special circumstances. In addition, saline agro-forestry adds organic matter in the soils. Therefore, permeability of soil increases which helps leaching of salts. Hence saline agriculture with drainage is a better combination of engineering and bio-saline measures and must be considered for adoption on large scale.

Treatment of Municipal Effluent

Municipal effluent in a mixed sewerage system (such as in Pakistan) generally includes wastewater flows from households, commercial enterprises, minor industrial units, and storm run-off during rains. Disposal of such sewage into canals, drains and rivers has attained an alarming magnitude all over the country, which is threatening the suitability of these water bodies for any use.

The disposal of sewage streams into fresh water channels and agricultural drains has been increased as a consequence of the growth of human settlements and associated commercial and industrial activities. The volume of sewage from the major cities of Pakistan discharged into the drainage system is more than 2580 mgd. The points of disposal are so numerous and scattered that treatment of all these streams will probably never be possible. However, in major towns and cities where large sewerage networks collect a large fraction of the sewage, the final outfall discharges should be subjected to treatment.

Provision of sewage treatment plants in some major cities is already at various stages of consideration and planning by District Governments and should be integrated with drainage development and water management plans of the individual basins.

Treatment of Industrial Effluent

Treatment of liquid and gaseous emissions to acceptable limits is the responsibility of the concerned industry. Each type of industry generates its own peculiar type of waste discharge depending upon the production and processes taking place. Treatment plants should therefore be designed specifically for each industrial unit, on the basis of its plant processes, production capacity and running schedule etc. The estimated quantum of industrial effluent of some major cities being discharged into drains is nearly 365 mgd.

The problem of disposal of industrial wastes into fresh water bodies can only be checked through strict compliance of the National Environmental Quality Standards (NEQS) and adoption of environmental management systems by industries like ISO 14000 etc.

The Provincial Irrigation and Drainage Authorities (PIDAs) must work with the Provincial Environmental Protection Departments to achieve compliance of NEQS in order to protect the quality of river and canal waters.

CONCLUSIONS

Irrigated agriculture is a matter of survival for the people of Pakistan and drainage indeed is mirror image of irrigation. Good and efficient drainage guarantees the survival of irrigated agriculture. However it is of utmost import that no environmental adverse effects are created by drainage measures.

Due to inherent salinity in surface water, groundwater and the soils, the matter of salt balance attains paramount importance. The issue needs to be viewed from different stand-points and ground conditions. The following points need to be considered while developing drainage plans:

(i) Drainage Development and Water Management Plans need to be prepared for each basin with the consultation and participation of beneficiaries/stakeholders.

(ii) The choice between tube-wells and subsurface pipe drainage needs to be made on salt load basis with due investigations. Generally piped drainage generates comparatively less effluent having lower salt contents than tube-well drainage.

(iii) Equitable distribution of canal water and better water management options to reduce drainage effluent should be adopted.

(iv) Efforts at reducing recharge from the canal system should be intensified especially in the saline ground water areas.

(v) Use of marginal quality drainage water on sustainable basis needs to be promoted with saline agriculture.

(vi) Municipal and industrial effluents need to be treated before joining the drainage system.

ABBREVIATIONS

BCM	Billion Cubic Meter
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
Ec	Electrical Conductivity
EPA	Environmental Protection Agency
FGW	Fresh Ground Water
GCA	Gross Commanded Area
IBIS	Indus Basin Irrigation System
IWASRI	International Waterlogging and Salinity Research Institute
KPOD	Kadenji Pateji Outfall Drain
LBOD	Left Bank Outfall Drain
LIA	Landhi Industrial Area
Mha	Million hectare
mgd	million gallons/day
NDP	National Drainage Programme
NEQS	National Environmental Quality Standards
NSDS	National Surface Drainage System
NWFP	North West Frontier Province
PIDA	Provincial Irrigation & Drainage Authority
RBOD	Right Bank Outfall Drain
RSC	Residual Sodium Corroborate
SAR	Sodium Adsorption Ratio
SCARPS	Salinity Control and Reclamation Projects
SGW	Saline Ground Water
SITE	Sindh Industrial Trading Estate
SMO	SCARP Monitoring Organization
WAPDA	Water & Power Development Authority

REFERENCES

Government of Punjab, Irrigation & Power Department, Directorate of Land Reclamation 2002, An Atlas, Industrial Pollution in Punjab Irrigation System, July 2002, Lahore.

Government of Sindh, Environmental Protection Agency, 2003, Communication Regarding Municipal and Industrial Effluent, August 2003, Karachi.

Ground Water Development Potential, Water Resources Planning, Directorate, WAPDA, 1988, Lahore.

IWASRI, Integrated Water Resources Management Programme for Pakistan-Surface Water Resources Study, 1998, Lahore. IWASRI Internal Report No. 98/1 pp. 153.

Ministry of Water and Power, GOP, NDP Sector Planning Studies – National Surface Drainage System (NSDS), Pre-feasibility Report, Volume-I & II, October 2002 by Indus Associated Consultants and Louis Berger International.

SMO, WAPDA, River Water Quality, 2001, Lahore.

SMO, WAPDA, Summary Evaluation and Monitoring Statistics of SCARPs. SMO Publ. No. SM-37, 1986, Lahore.

T&K, Report on Groundwater and Reclamation Programme, Project No. 6 Panjnad Abbasia Area.

WAPDA, 2005, Drainage Master Plan of Pakistan by IWASRI and Planning & Design Division, Water Wing WAPDA, December, 2005, WAPDA House, Lahore.

WAPDA, Control of Waterlogging and Salinity by WAPDA National Seminar on Waterlogging and Salinity, March 20-21, 1986, Lahore.

WAPDA, Drainage Sector Environmental Assessment (DSEA), WAPDA, 1993, Lahore.

WAPDA, HARZA Master Plan by HARZA International, WAPDA, 1963, Lahore.

WAPDA, Lower Indus Report by Hunting-Mot MacDonald, 1966, Lahore.

WAPDA, NESPAK-ILACO, 1981. Final Plan, Panjnad Abbasia Salinity Control and Reclamation Project (SCARP-VI) Report, March 1981, Lahore.

WAPDA, NESPAK-Mot MacDonald, Feasibility Study, National Drainage Programme-I, Volume-I & II, May 1995.

WAPDA, Pakistan Drainage Consultants (PDC), Lahore. Monthly Progress Report No. 50.

WAPDA, Planning Division, Irrigated Agriculture Final Report, April 1982.

WAPDA, Revised Action Programme (RAP), May 1979, Lahore.

WAPDA, Right Bank Master Plan by Hunting Technical Services, 1992.

WAPDA, Water Resources Planning Organization, (WRPO), Water Sector Investment Planning Study (WSIPS), Water Sector Investment Planning Study, December, 1990.

WAPDA, Watertable Data (1993-2002) by Salinity Control and Reclamation Project Monitoring Organization, Lahore.

CHANGE OF IRRIGATION WATER QUANTITY ACCORDING TO FARM MECHANIZATION AND LAND CONSOLIDATION IN KOREA

Wook Jong Ju[1]
Jin Taek Kim[2]
Hyun Young Kim[3]

ABSTRACT

Since 3000 BC, rice has been the main crop in the Korean Peninsula, and where currently most of the available irrigation water is used to grow paddy rice. Methods for calculating the quantity of irrigation water required developed in the 1990's were compared to quantities measured in the field. The largest difference between calculated and measured quantities occurred in April and May. Based on field data we obtained in the middle part of the Korean Peninsula, significant changes have occurred in rice management, which has changed the amount of irrigation water required. Rice is now transplanted earlier, and duration of the transplanting phase on the regional scale is shorter through mechanization and consolidation of land holdings. These changes need to be taken into account when calculating the quantity of water needed for irrigation.

INTRODUCTION

The Comprehensive plan of water resources in Korea says that 48% of water resources are used for agricultural purpose. And except for river maintenance flow, 62% of water resources are used for same purpose. So, it is very important to carefully manage agricultural water in order to use water resources efficiently.

Since 1970, the manufacturing sector of the economy has grown rapidly. Also the agricultural work force has declined; there are fewer people left in farming villages. To replace this source labor, farming operations have been mechanized and the land holding managed by individual farmers has increased.

These changes have influenced the management of irrigation water. The pattern and quantity of supplying irrigation water has been changed. Some reports have quoted this existing condition. The report "Study on Improvement of Rural Water Supply and Operation of the Experimental Site" says that the ratio of planning quantity of irrigation water to actual supplying quantity is over 1.3 (Rural Research Institute, 2002; Korea Institute of Construction Technology, 2001). The disparities between two quantities in April and May are larger than other months.

---

[1] Researcher – Rural Research Institute, KRC, Korea; 1031-7, Sa-Dong, Ansan-Si, Gyeonggi-Do, Rep. Of Korea, 426-908; juj11@ekr.or.kr
[2] Senior Researcher –Rural Research Institute, KRC, Korea; 1031-7, Sa-Dong, Ansan-Si, Gyeonggi-Do, Rep. Of Korea, 426-908; jtkim@ekr.or.kr
[3] Director General of Rural Research Institute – Rural Research Institute, KRC, Korea; 1031-7, Sa-Dong, Ansan-Si, Gyeonggi-Do, Rep. Of Korea, 426-908; hykim@ekr.or.kr

The purpose of this study is to revise the methods of estimating the quantity of irrigation water required for paddy rice to properly account for the changes in rice management that have occurred.

CHANGE OF CULTIVATING METHODS

Rice cultivating technologies have been developed in step with social and economic situation in process of time since the prehistoric age in Korea. In the Neolithic era, the upland rice is cultivated by the method of direct seeding in dry field. At the close of the Corea Dynasty (15th century), the technology of transplanting began to be used. Until 1970s, transplanting by human strength is the major method to cultivate rice.

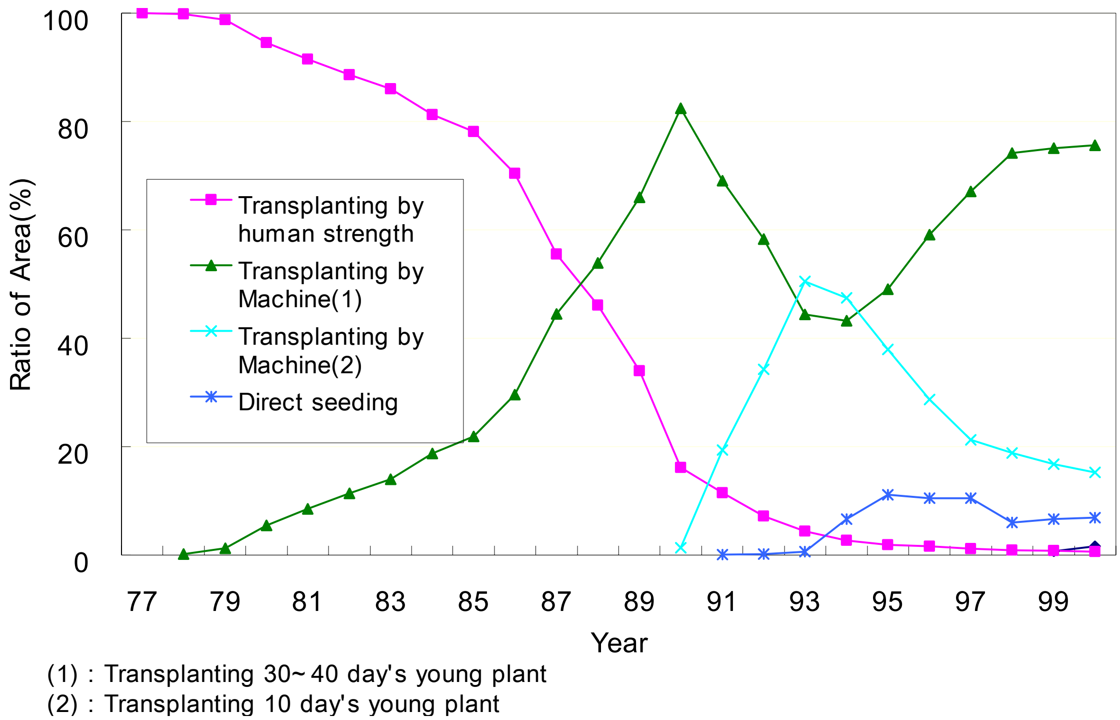


Figure 1. Variation of methods to cultivate rice in paddy field

From the end of 1970s, Korea has been industrialized and urbanized, and the number of people available to transplant rice became limited. It was necessary to cultivate using machine and consolidate land to use machine. By 1988, Farmers was used machine to transplant more than 50% of the area planted rice (Figure 1). By 1994 this increased to 90.8%.

These variations have changed the date of rice growing stages and the quantity of irrigation water for rice in paddy field.

CURRENT METHOD TO ESTIMATING IRRIGATION WATER DEMAND

Irrigation water's major purpose is to supply water for growing rice healthily. Irrigation water quantity is influenced strongly by weather conditions such as precipitation and evapotranspiration.

Current methods to estimate irrigation water demand has been developed from 1910s. The system for estimating irrigation water demand is HOMWRS(Figure 2), which was established using data collected 20 years ago. The inputs of HOMWRS are total beneficial area, area by methods of cultivating rice, ratio of water loss in irrigation canal, percolation, ET data etc.

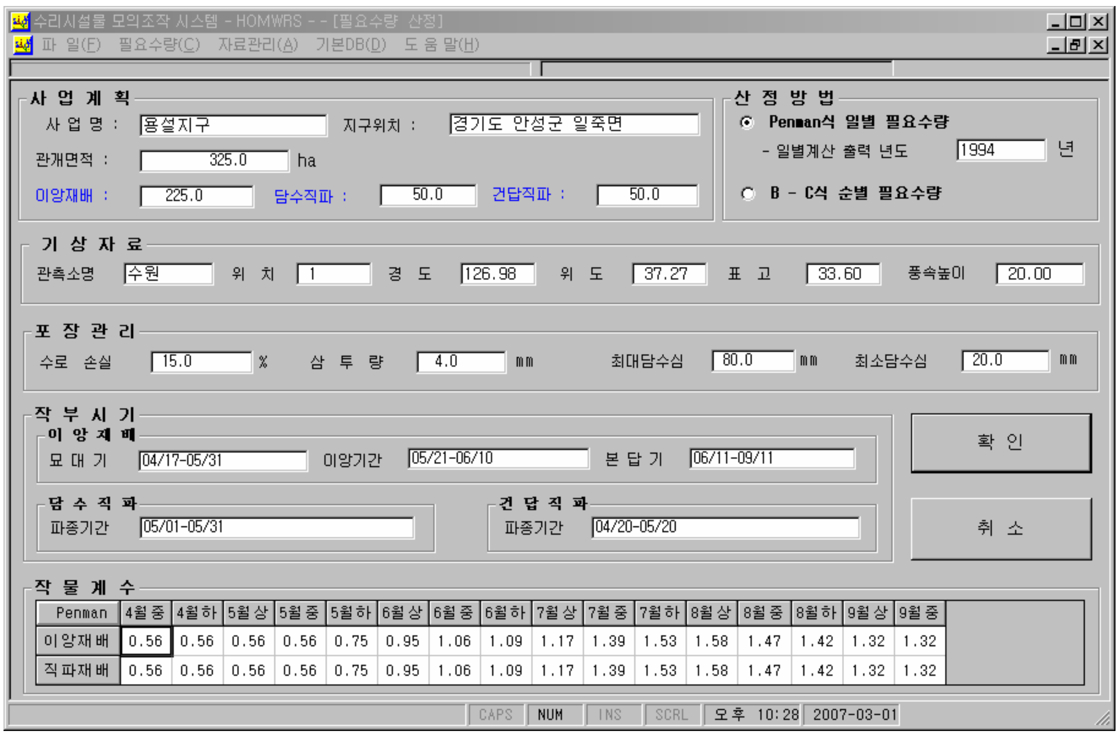
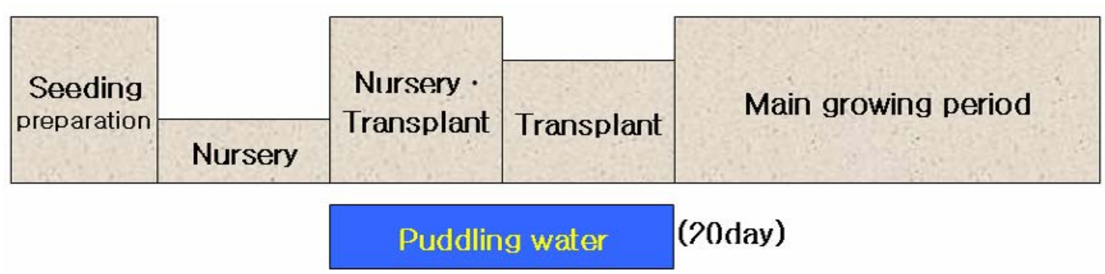


Figure 2. System to estimating irrigation water demand (HOMWRS)



Puddling water: water which should be supply before transplant

Figure 3. Stages of cultivating rice

Table 1. Dates of growing stages – rice (Month / Day)

Region	nursery	transplant	Main growing period
Central Region	4/17 ~ 5/31	5/21 ~ 6/10	6/11~9/11
Southern Region	4/27 ~ 6/10	6/1 ~ 6/20	6/21~9/21

The time step of this system (HOMWRS) is one day. This system calculates the irrigation water demand by analyzing water balance in paddy field. The consumption factors are evapotranspiration, infiltration and water losses in canals. The supplying factors are precipitation and water supply. There are 3 stages to cultivate rice(Figure 3 and Table 1). The methods to supply irrigation water are different from one another.

EXPERIMENTAL SITE AND RESEARCH METHODS

Experimental Site

In order to measure the quantity of actual irrigation water, we chose one experimental site, Yi-dong Reservoir district which is located in central region of Korea. The area of this watershed is 9,300 ha. The beneficial area of Yi-dong reservoir is 2,063ha. There are two reservoirs in Yi-Dong reservoir's watershed, Yong-deok reservoir and Mi-san reservoir. There are two pumping station in the beneficial area – Eun-san pumping station and Won-dam pumping station . There are five main canal in this district - Jin-Wie main canal, Jin-Won main canal etc. These facilities are managed by KRC (Korea Rural Community & Agriculture Corporation)

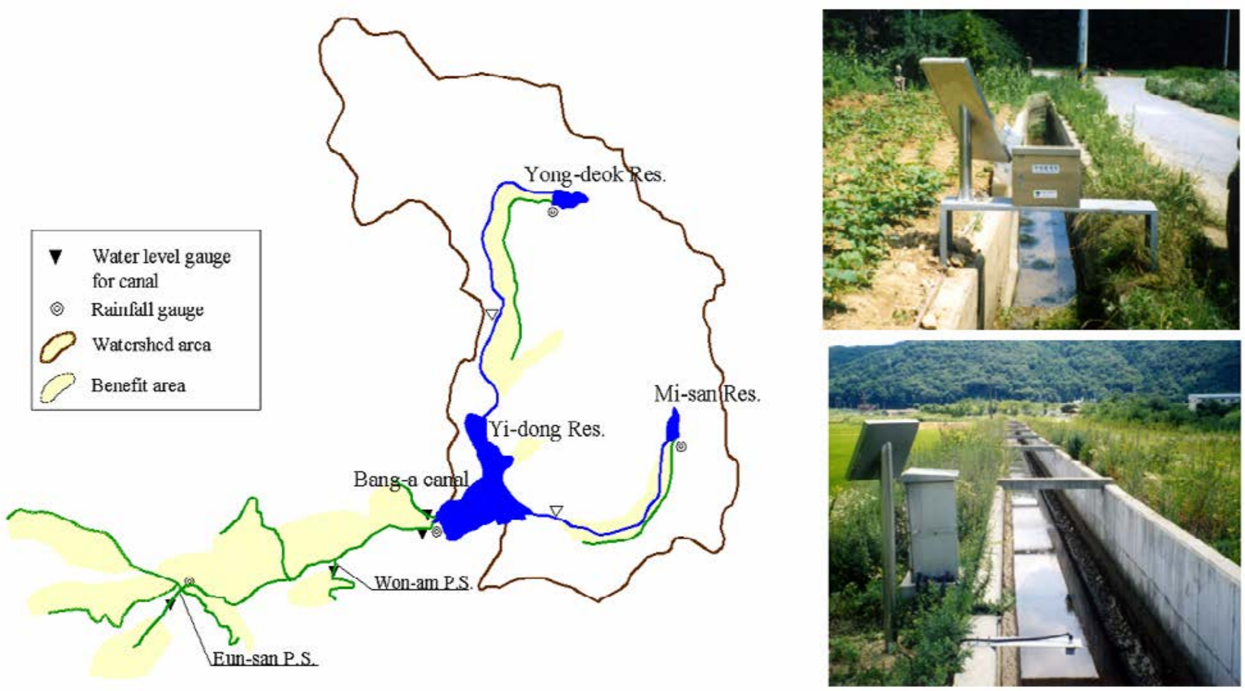


Figure 4. Yi-dong experimental site and water level measuring system in canals

Table 2. Characteristics of the irrigation canal

Canal (District classification)	Beneficial area	Facility to supply	
		Name	Watershed area
Jin-Wie main canal	2,063ha	Yi-dong Res.	9,300 ha
Jin-Won main canal	1,286ha	Eun-san P.S.	-
Bang-a secondary canal	128ha	Yi-dong Res.	9,300 ha

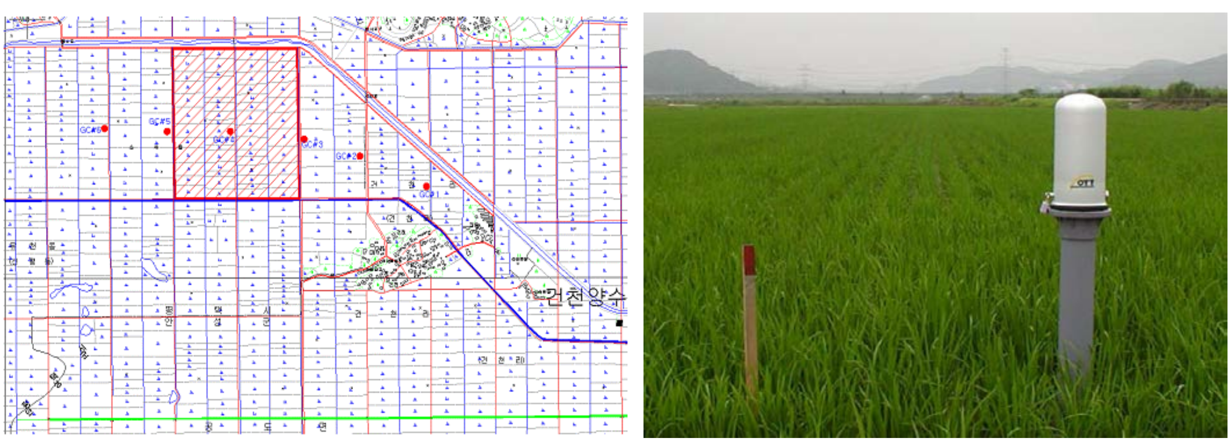


Figure 5. Equipment for measuring water level in paddy field

Research Methods

In order to measuring the supplying water quantity, three water level gauges were installed in three canals. – Jin-Wie main canal, Jin-Won main canal and Bang-a secondary canal. Water resource of Jin-Wie main canal is Yi-Dong reservoir, Jin-Won main canal is Eun-san pumping station, Bang-a secondary canal is Yi-dong reservoir.

We measured the quantities of water flowing through these canals using flow meter. We found out the relation between water level and water quantity. So, the quantity of supplying irrigation water through these canals was calculated.

In order to know the periods of 3stages of rice growing, we monitored the proceeding ratio of transplanting and the proceeding ratio of supplying transplanting water. The proceeding ratio of transplanting is the transplanted area divided by total beneficial area. The proceeding ratio of supplying transplanting water is the area supplied transplanting water divided by total beneficial area.

We installed equipment for measuring water level (ponded depth) in paddy field in order to know the characteristics of managing water in paddy field by farmers. This equipment was installed at seven locations in Yi-dong experimental district.

We analyzed the characteristics of irrigation water management and make a comparison between practical situation in field and current system for estimating irrigation water quantity.

RESULTS

Supplying water for transplanting and transplanting

There are no areas of direct seeding in central region of Korea. The major method of cultivating rice is transplanting using machinery. Most of rice is same species – Chuchung. The results of monitoring the proceeding ratio of supplying transplanting water and the proceeding ration of transplanting (Figure 6 and Figure 7).

Results of investigating practical date of rice growing stages are shown in Table. 3. The practical starting date of stage is earlier than the criteria date of current method which estimates irrigation water quantity. The period of the transplant is shorter than the previous.

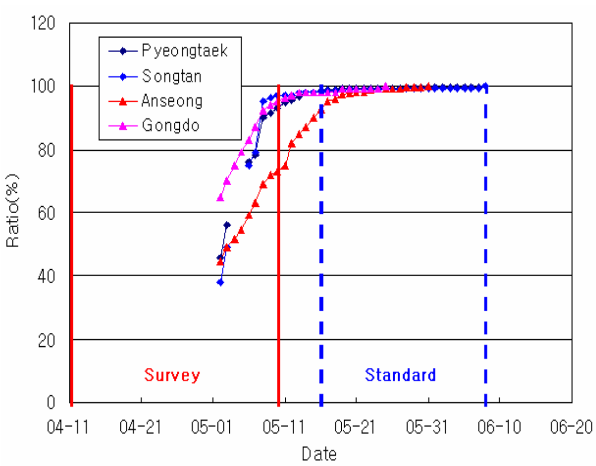


Figure 6. Proceeding ratio of supplying transplanting water

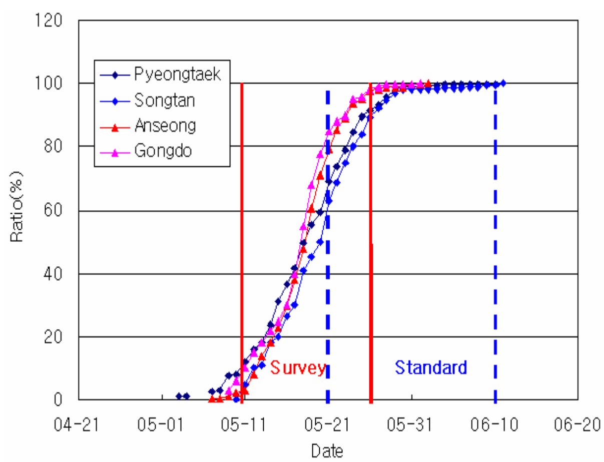


Figure 7. Proceeding ratio of transplanting

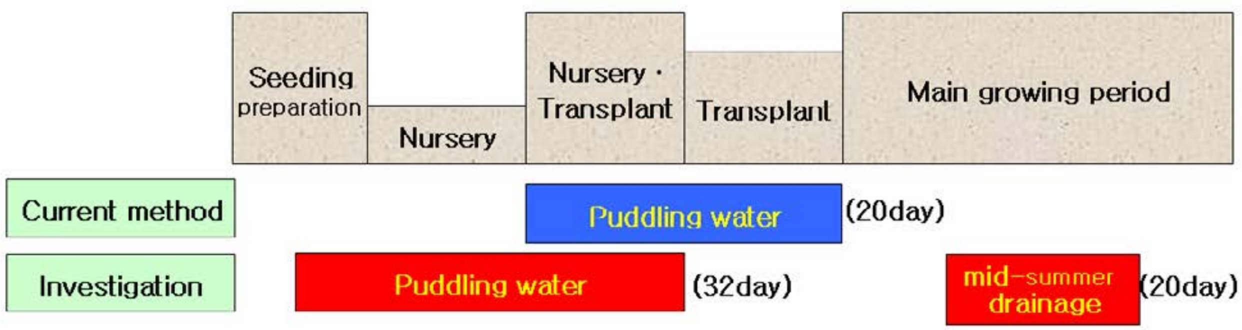


Figure 8. Practical stages of rice growing

Table 3. Practical date of rice growing stages (Month / Day)

Classification	Nursery	Transplant	Main growing period
Current Method criteria	4/17 ~ 5/31	5/21 ~ 6/10 (21day)	6/11 ~ 9/11
Investigation Results	4/11 ~ 5/18	5/12 ~ 5/26 (15day)	5/27 ~ 9/11

Water Level (Ponding Depth) in Paddy Field

The results of measuring water level in paddy fields are shown in Figure 9. Figure 9 says that mid summer drainage are practiced in most of paddy field. The period is between 26th June to 12th July.

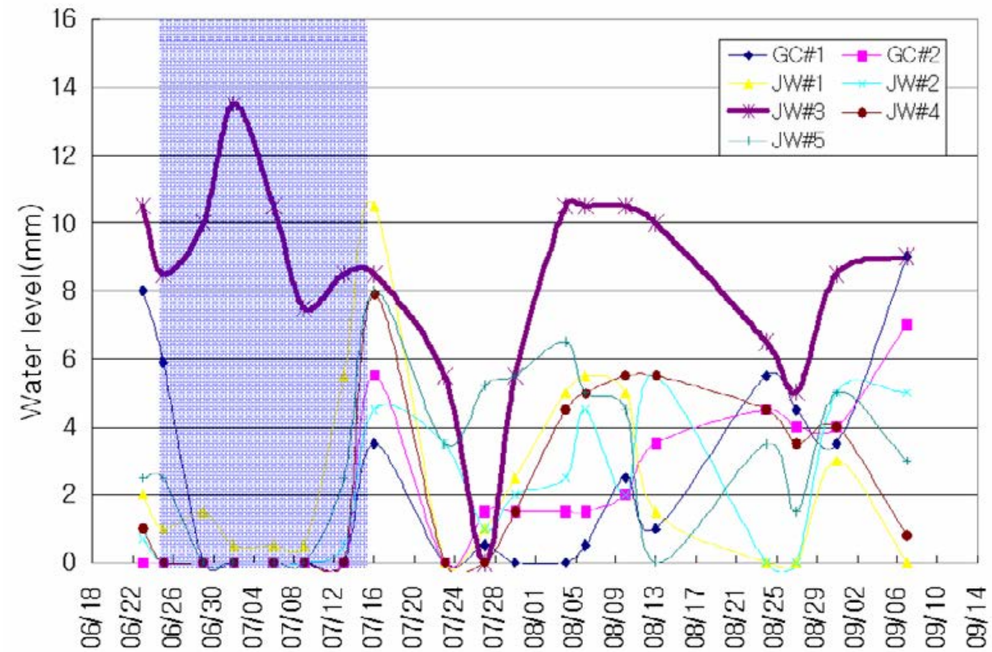


Figure 9. Water level (ponding depth) in paddy fields

The Quantity Of Supplied Water In Experimental Site

Table 4 and Table 5 show the supplied water discharge measured in Jin-Wie main canal, Jin-Won main canal and Bang-A secondary canal.

The supplied water discharge in 2004 was more than 2003. It is because that the amount of rainfall in 2004 is less than 2003. The quantity of supplied water in May was more than any other month. It is because there are few rainfall in spring and puddling water is supplied in April and May.

Table 4. Supplied ater (2003)
Unit : 1000 ㎥

Month	Jin-Wie	Jin-Won	Bang-A
Apr	4,696	843	421
May	9,573	3,055	836
Jun	6,273	2,290	660
Jul	2,703	292	59
Aug	4,093	708	543
Sep	20	0	0
Total	27,357	7,188	2,519

Table 5. Supplied water (2004)
Unit : 1000 ㎥

Month	Jin-Wie	Jin-Won	Bang-A
Apr	4,146	1,372	424
May	8,651	3,591	890
Jun	5,775	2,100	690
Jul	2,289	688	275
Aug	7,004	2,145	868
Sep	1,717	690	237
Total	29,564	10,586	3,384

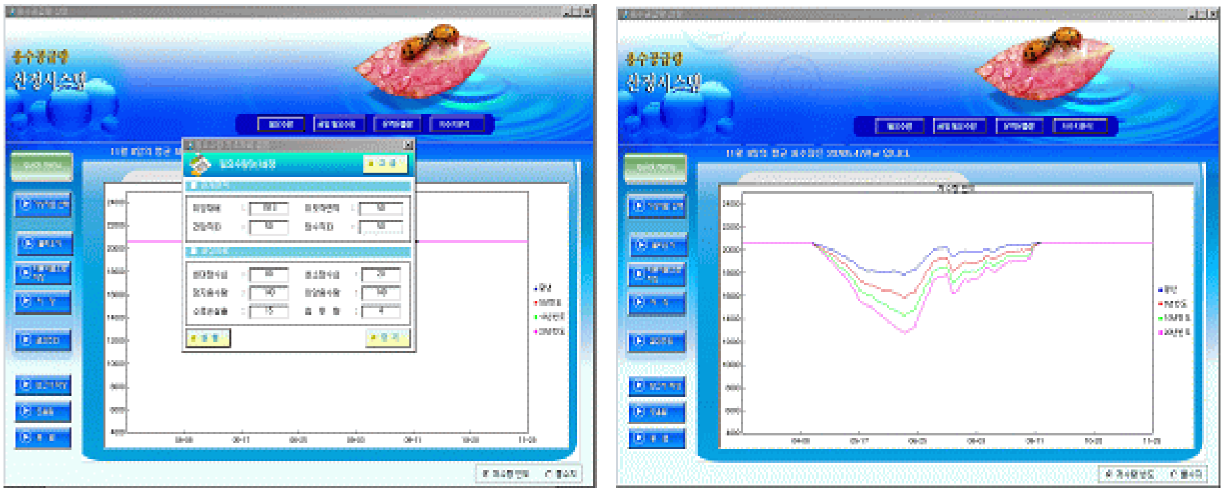


Figure 10. New system to estimate irrigation water demand

Calculating The Quantity Of Irrigation Water In Paddy Field

Considering the investigated data, new system to estimating irrigation water demand was developed. (Figure 10)

In order to compare new system to current system (HOMWRS), We calculated irrigation water demands using two system. We called Case 1, in case of using current system and called Case 2, in case of using new system. The period of supplying puddling water is 32days, But it is efficient to shorten the period of supplying puddling water in order to save water resources. So we make Case 3, in which the period of supplying puddling water is 20 days. The dates of rice growing stages for three cases are shown in Table 6.

Table 6. Dates of rice growing stages for cases

Case	nursery	transplant	Main growing priod	Puddling water	mid summer drainage
I	4/17 ~ 5/31	5/21 ~ 6/10	6/11 ~ 9/10	5/21 ~ 9/10	-
II	4/11 ~ 5/18	5/12 ~ 5/26	5/27 ~ 9/10	4/13 ~ 5/18	6/26 ~ 7/12
III	4/11 ~ 5/18	5/12 ~ 5/26	5/27 ~ 9/10	4/29 ~ 5/18	6/26 ~ 7/12

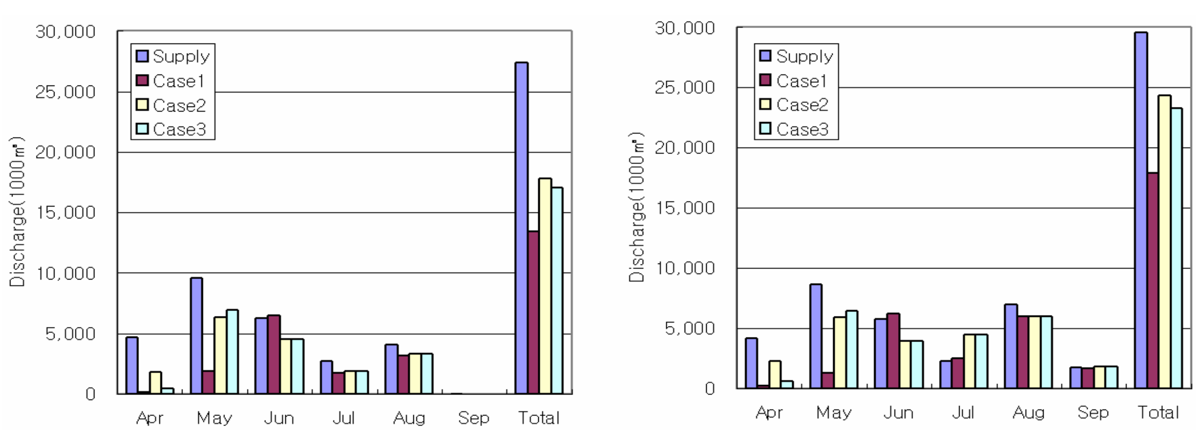
Table 7. Ratio of water supply discharge to estimated discharge for 3 cases

district	Supply/Case 1			Supply/Case 2			Supply/Case 3		
	2003	2004	Avg	2003	2004	Avg	2003	2004	Avg
Jin-Wie	2.03	1.65	1.84	1.54	1.21	1.38	1.60	1.27	1.44
Jin-Won	0.93	1.02	0.97	0.70	0.75	0.73	0.73	0.79	0.76
Bang-A	2.91	2.94	2.93	2.20	2.16	2.18	2.29	2.26	2.28
Avg			1.91			1.43			1.49

The ratios of water supplied to estimated discharge by three cases are shown in Table 7. The average ratio of 'Supply/Case1' is 1.91. The average ratio of 'Supply/Case2' is 1.43. These show that water is supplied more than estimated quantity. It is inferred that water losses is larger than the figure we applied to systems calculating the irrigation water demand. But we know that case 2 was estimated more similar to the practical supplied water.

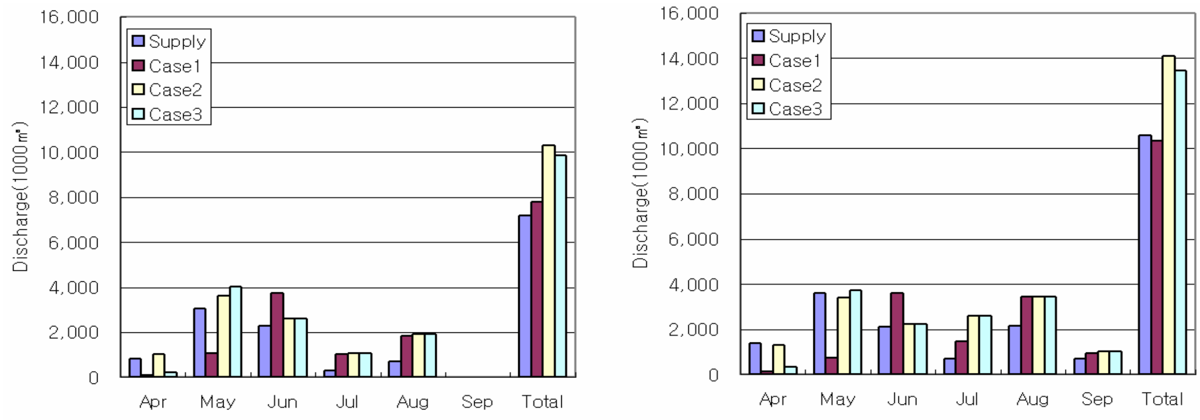
Figure 11, Figure 12 and Figure 13 shows that the amount of irrigation water. In Case 1, the disparity between supplied water and estimated water is much larger than in Case 2. Most of disparity occurred in April and May. The pattern of estimated water demand by Case 2 through month is more similar to practical supplied water than by Case 1.

The water quantity of estimated by Case 3 is equal to the estimation of Case 2 in Jun, July, Aug and September. But the ratio of water quantity divided by Case 2 and Case 3 is 1.05. So we inferred that we can save water 5% by decreasing period of supplying puddling water from 30 days into 20 days.



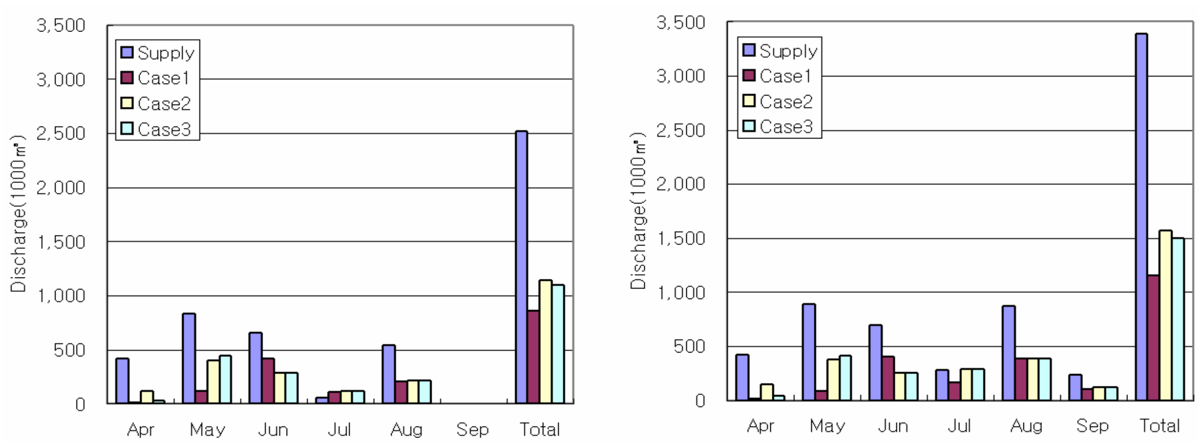
(a) 2003 (b) 2004

Figure 11. Water supply and water demand (Jin-Wie)



(a) 2003 (b) 2004

Figure 12. Water supply and water demand (Jin-Won)



(a) 2003 (b) 2004

Figure 13. Water supply and water demand (Bang-A)

CONCLUSION

The main purpose of this study is to develop proper method to estimate irrigation water quantity. To do so, we investigate cultivating behavior in paddy field, compare to current system of estimating irrigation water quantity and developed the system to estimate irrigation water quantity considering practical field condition.

The summarized results are as follows.

1. The practical starting date of stages is earlier than the criteria date of current method which estimates irrigation water quantity. The period of transplant is shorter than it of current method.

2. Mid summer drainage are practiced in most of paddy field. The period is between 26th June to 12th July.

3. The system developed in this study was estimated more similar to the practical supplied water than the current system in use.

4. 5% water could be saved by decreasing the period of supplying puddling water from 30 days into 20 days.

But we cannot calculate the irrigation water quantity more accurately because water losses in irrigation canals and crop coefficient are not determined appropriately. So, it is necessary to study on irrigation canal losses and crop coefficient in future.

REFERENCES

1. Si-Won Kim, Chung-Ki Kim, Gi-Chun Lee. 1996. Shin-Go agricultural hydrology. Hyangmunsa.

2. Rural Research Institute – KRC. 2002. Study on Improvement of Rural Water Supply and Operation of the Experimental Site: Korea.

3. Korea Institute of Construction Technology. 2001. Study on improving methods of water management efficiency: Korea.

4. Rural Research Institute – KRC. 2005. A Study on Water Supply Methods Considering Variation of Farming Conditions in Paddy Field: Korea.

5. Ministry of Agriculture & Forestry, KRC. 1999. Comprehensive Report about agricultural water: Korea.

6. Jin Taek Kim, Wook Jong Ju, Ki Wook Park, Jong Nam Lee. 2005. Estimation of the water requirement with the farming conditions in paddy field. Korea Water Resources Association: Korea.

7. Ministry of Agriculture & Forestry, KRC, 2006. A Study on proper Management of Agricultural Canal System for Efficient Water Use:, Korea.

8. Wook Jong Ju, Jin Taek Kim, Ki Wook Park, Yong Jik Lee. 2006. Develoment of System for Estimating Water Demand Considering Variation of Farming Conditions in Paddy Field. KCID Journal 13(1): 33-47.

APPLICATION OF GEOSPATIAL TECHNOLOGIES FOR SUSTAINABLE IRRIGATION AND RECLAMATION OF SALINE SOIL

Dr. J.N. Patel[1]

ABSTRACT

Major portion of the rainwater goes to ocean as runoff via network of manmade as well as natural drains. The rainwater going as waste can be utilized for sustainable irrigation by improvement of groundwater quality and reclamation of saline soils. In this paper the application of geospatial technologies has been discussed for making strategy for improvement of groundwater quality and reclamation of saline soil. The strategy include the application of geospatial technologies for management of rainwater and its harvesting by (i) diverting the rainwater to the groundwater by various techniques of artificial groundwater recharge to increase the quantity and to improve the quality of groundwater for irrigation and other purposes, and (ii) diverting the rainwater to irrigation fields for the purpose of leaching for reclamation of saline soil. The techniques shown in (i) or (ii) or both may be used depending upon the site conditions and other affecting parameters. The geospatial technologies like remote sensing, GIS and GPS can be applied for the purpose of preparing strategy. Above indicated strategy has been discussed in this research paper with their multi advantages. A case study of Surat (India) is also included in the paper to highlight the application of geospatial technologies.

INTRODUCTION

The rainwater is the great source of water on the earth, majority of which goes as a waste. It can be utilized properly to meet the need of water for various purposes on the earth. There is some environmental benefit of maintaining certain minimum flow and flow regimes in rivers. The rainwater and flood water can be utilized for sustainable irrigation and reclamation of saline soil effectively if managed properly. Storage of groundwater is one of the aspects for sustainable irrigation, which can be achieved through artificial groundwater recharge. Artificial groundwater has many advantages like improvement of groundwater quality, reduction in floods, storage of water under ground etc. Planning for artificial groundwater recharge plays a vital role for achieving the optimum benefits. The harvested rainwater or the floodwater can be used for artificial groundwater recharge. There is also a need of reclamation of saline soils. The cheapest way of reclamation of saline soil is to use the rainwater or flood water for leaching. Leaching of saline soil using floodwater or harvested rainwater has also many advantages like improvement of soils, diversion of flood on overland, reduction in the effects of floods etc. Geospatial technologies can be effectively used for planning of such activities. Geospatial technologies like remote sensing, geographical information system and global positioning system are commonly used now a days for planning of such water resources engineering activities. With the use of such technologies it becomes very easy and economical to plan and implement any water resources engineering project. Strategy for sustainable irrigation, management and harvesting the rainwater

[1] Professor of Civil Engineering; Sardar Vallabhbhai National Institute of Technology; SURAT – 395 007; INDIA
jnp@ced.svnit.ac.in, jrgpk@yahoo.co.in

and leaching of saline soil using rainwater or flood water can be prepared using such technologies effectively.

SUSTAINABLE IRRIGATION

Sustainable irrigation can be achieved by one or more of the following measures.

1. Storage of rain / flood water under ground which goes as waste otherwise, in addition to storage of rain water in reservoirs, ponds, tanks and other means
2. Use of rain / flood water for leaching for reclamation of saline soil
3. Conjunctive use of surface and groundwater
4. Efficient drainage system for salt removal from agricultural fields
5. Improvement in quality of groundwater
6. Improvement of fertility and productivity of agricultural land
7. Low cost generation of agricultural products

Excess rainwater and flood water can be utilized to achieve one or more of the above purposes. This can be done by proper planning and management of water resources, which in turn, proves to be very much advantageous in long run.

ARTIFICIAL GROUNDWATER RECHARGE

Methods of Artificial Groundwater Recharge

Storage of underground water is possible through various techniques of artificial groundwater recharge, which is helpful for improving the quality of groundwater and increasing the storage of groundwater. Artificial recharge of groundwater is possible by the following techniques.

1. Artificial recharge of groundwater through existing tube wells or open wells.
2. Artificial recharge of groundwater through specially designed recharge wells.
3. Construction of storm water drainage system in conjunction with groundwater recharge.

Artificial recharge of groundwater is suggested by two different ways. First way is to divert the rainwater from roof / terrace of houses to existing or specially designed recharge wells. Second way is to divert the runoff water to existing or specially designed recharge wells. Figure 1 shows the method developed for artificial groundwater recharge through existing tube wells. Figure 2 shows the method developed for artificial groundwater recharge through newly constructed tube wells.

It is also possible to design the storm water drainage system in conjunction with groundwater recharge well in the new developing areas, where the storm water drainage system is not existing. A part of the storm water can be diverted to the groundwater through specially designed recharge well as shown in Figure 3, which also lead to saving in initial cost of construction of such system.

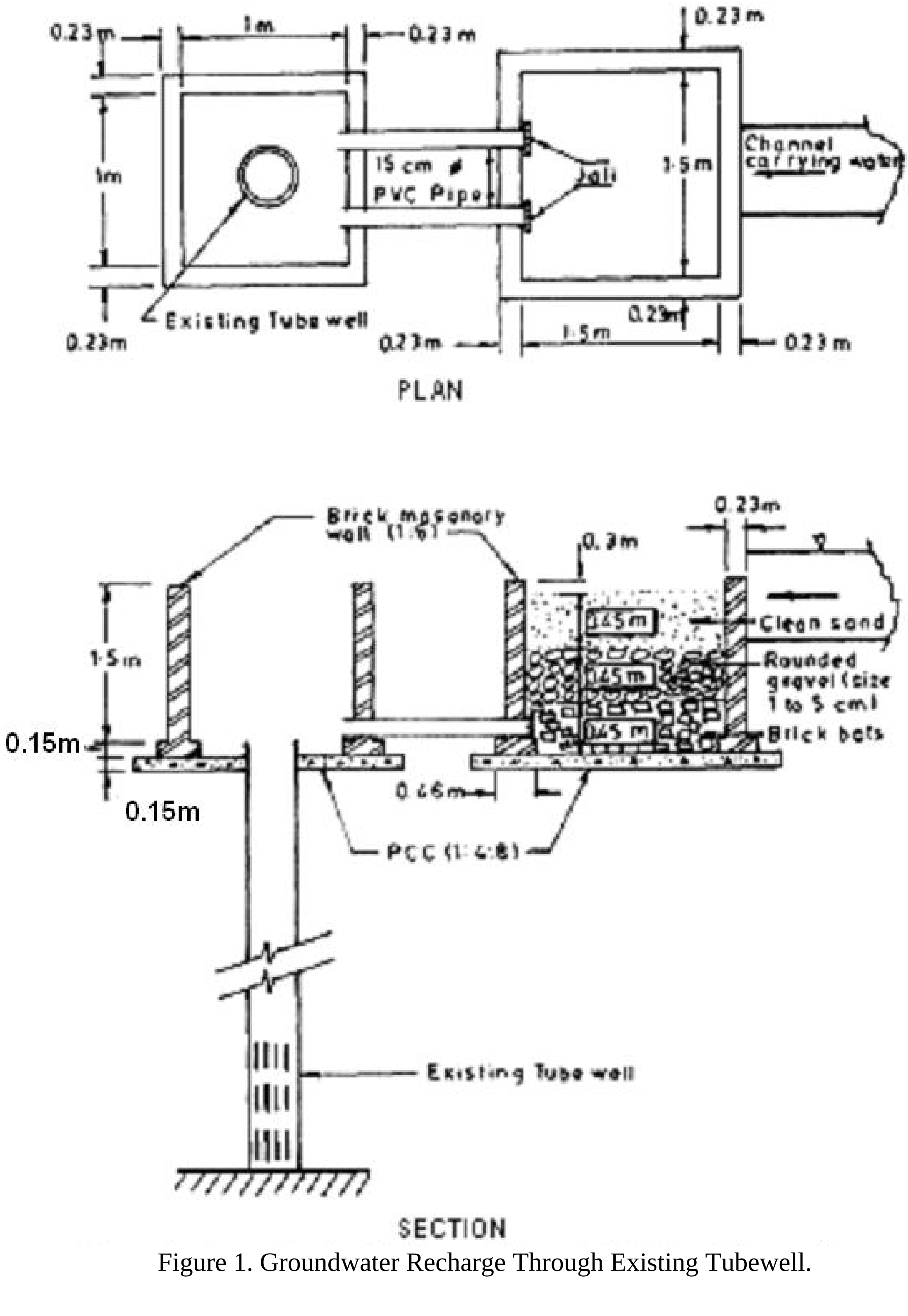


Figure 1. Groundwater Recharge Through Existing Tubewell.

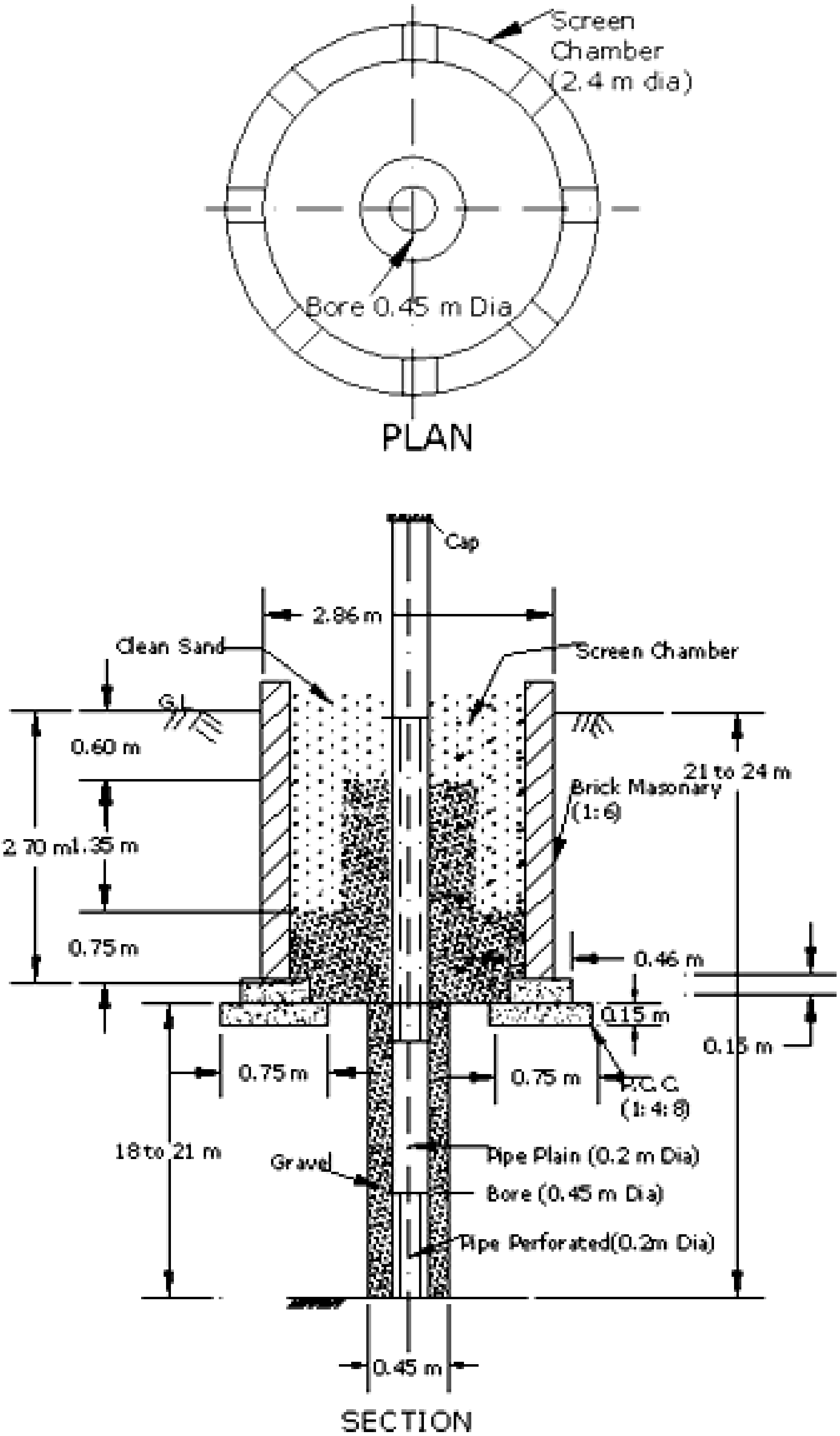


Figure 2. Method of Recharging in a New Tubewell.

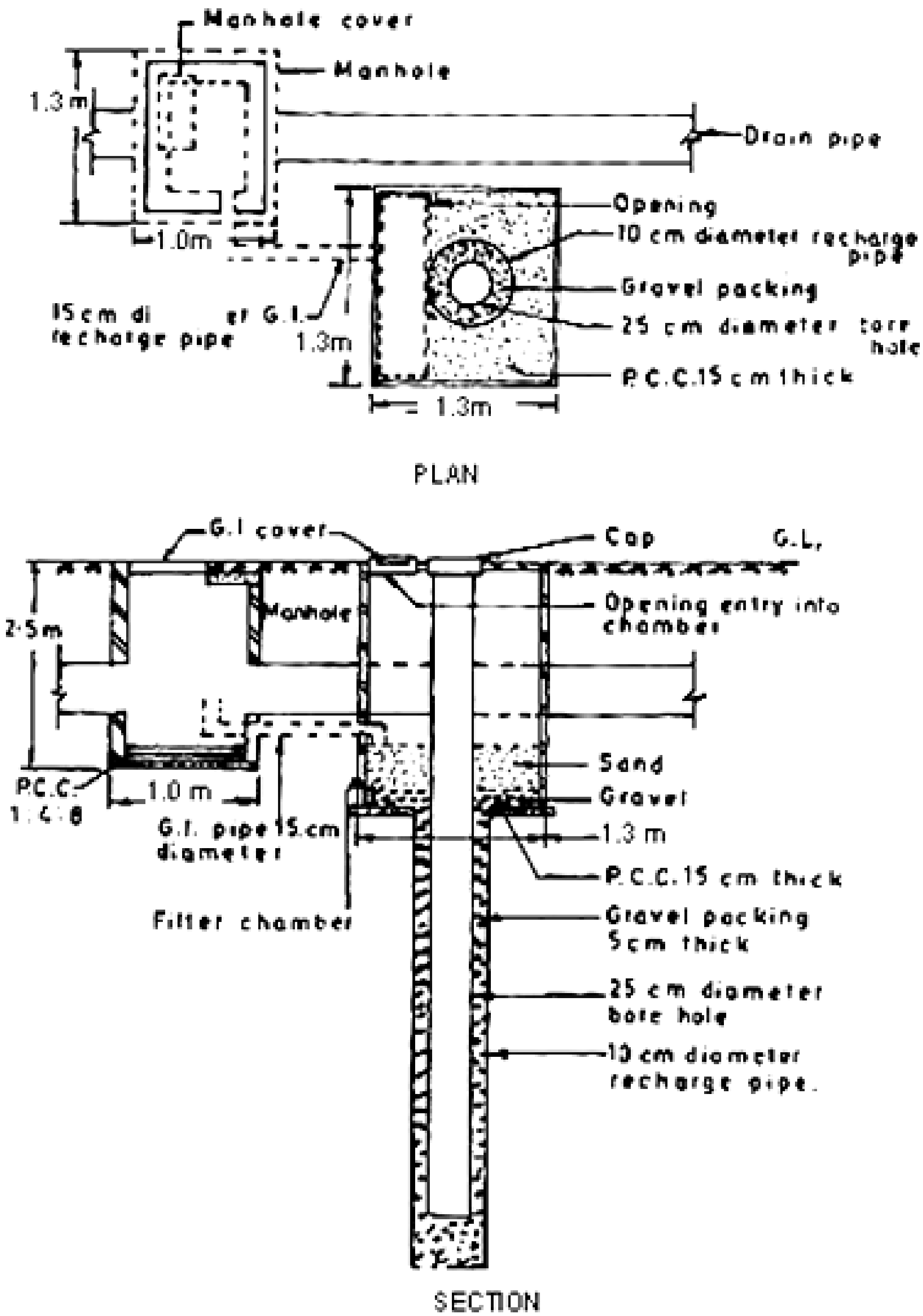


Figure 3. Groundwater Recharge Well with Stormwater Drainage System.

Pilot Projects and Results

A research project was implemented to study the effect of artificial groundwater recharge on quality of groundwater and increase in ground water storage. Another research project was carried out to study the economical analysis of the storm water drainage system in conjunction with groundwater recharge. The details of the projects are discussed below.

Effect of Artificial Groundwater Recharge : Five numbers of the artificial groundwater recharge wells were constructed at the campus of S.V. Regional College of Engineering and Technology situated at Surat, India. A map of the area indicating location of the existing and recharge wells is shown in Figure 4. Samples of ground water were collected at different times from the ground water recharge wells and also from the existing wells in their vicinity and analyzed in the laboratory to study the effect of artificial recharge on quality of ground water. Also the changes in the rise of ground water level at the same wells were measured to study the effect of ground water recharge on increase of storage of ground water. Some of the results are summarized in Table 1 and Table 2. The estimated volume of water recharged through each recharge well was 15000-30000 m^3 per year. The existing well E4 which was recharged (well R4) is an unconfined well, where as the existing well E6 is a confined well.

Table 1. Change in Groundwater Quality in the Recharged Well R4

Sr. No.	Parameter	Value before recharge	Value after one year of recharge	Value after two years of recharge
1	pH	8.2	7.0	7.5
2	Chlorides (mg/lit.)	550	90	30
3	Total hardness (mg/lit)	399	200	200
4	Depth of water table below ground level (meter)	10.67	10.06	9.45

Table 2. Change in Groundwater Quality in an Existing Well E6 Situated 105 m away from Recharged Well R1

Sr. No.	Parameter	Value before recharge	Value after one year of recharge	Value after two years of recharge
1	pH	8.2	7.8	7.2
2	Chlorides (mg/lit.)	3798	3575	2650
3	Total hardness (mg/lit)	3520	3200	3000
4	Depth of water table below ground level (meter)	14.63	14.17	13.72

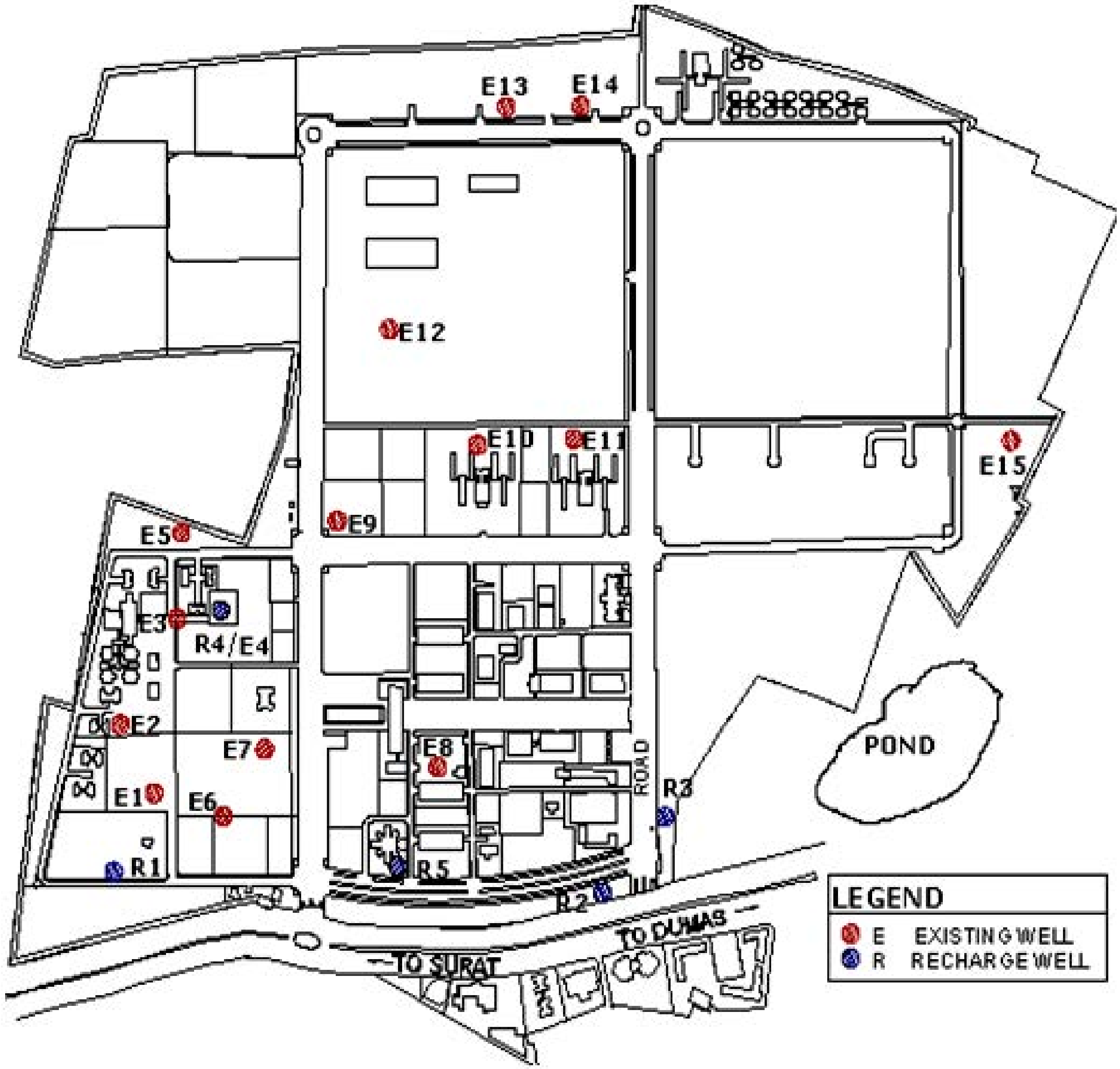


Figure 4. Location of Existing and Recharge Well.

From Table 1 it is clear that there is a considerable reduction in chlorides and hardness of water in the recharged tube well R4. The groundwater level also rose due to recharge at the well. There is also an improvement in the pH value of the groundwater. As shown in Table 2, there is also an improvement in the quality of groundwater in the wells situated to nearby vicinity of the recharge wells. A same trend in the change in groundwater quality and rise in the depth of groundwater level was observed in the other wells also. More and more improvement is seen after every monsoon season. The chlorides and hardness are found much higher in the confined wells due to seawater intrusion in the aquifers.

Economical Aspects of Storm water Drainage in Conjunction With Artificial Recharge: In the other project it was proposed to construct the groundwater recharge wells at every manhole of the storm water drainage system at newly developing areas of the city. The design of storm water drainage system in conjunction with groundwater recharge wells of different diameters was carried out. The study for economical aspects of the storm water drainage systems with groundwater recharge well and without groundwater recharge wells was also carried out. Suitable design of groundwater recharge well was done for the site conditions. Details of the groundwater recharge well to be used in conjunction with storm water drainage is shown in Figure 3. The computed rates of recharge for different diameters of wells were varying from 0.022 m^3/sec to 0.088 m^3/sec depending upon diameter of wells.

Total estimated costs for storm water drainage systems without groundwater recharge and with groundwater recharge wells of different sizes were computed. The cost of groundwater recharge well increases with the increase in the diameter of the recharge well. The total cost of the storm water drainage systems in conjunction with groundwater recharge well is found minimum when the diameter of the ground water recharge well is 50 cm in the situations under consideration. The savings in cost of the storm water drainage system in conjunction with groundwater recharge is varying from 5.8 % to 9.2 % as compared to storm water drainage system without groundwater recharge. The highest value of percentage saving is 9.2 % when the diameter of the recharge well is kept 50 cm.

Apart from the saving in initial cost, there is another advantage of improvement in quality of storm water passing through the filter media. The concentration of total suspended solids reduce when the storm water pass through the screen chamber of the groundwater recharge well. The hardness and chlorides also decrease due to groundwater recharge. The filter media need to be cleaned or to be replaced at regular intervals.

LEACHING FOR RECLAMATION OF SALINE SOIL

In the leaching process the rain water or flood water of low salt concentration is applied to displace the soil solution of relatively high concentration of salts. The water passing through the soil strata pushes the salts below the root zone or to the tile drains provided for the purpose of drainage. Thus, it is useful for reclamation of saline soil. Leaching is also useful for maintaining the salt balance in the reclaimed or irrigated land. Figure 5 shows the process of leaching using excess rainwater or floodwater.

Excess rain water or the flood water from the rivers and catchment area can be diverted to the agricultural fields where the soil has become saline. This water can be stored over the agricultural fields between soil bunds of required height for removal of salts from the soil strata through natural leaching process. The leached water at the end either goes to ground water bodies or it can be disposed to drains by sub surface drainage systems depending upon the site conditions.

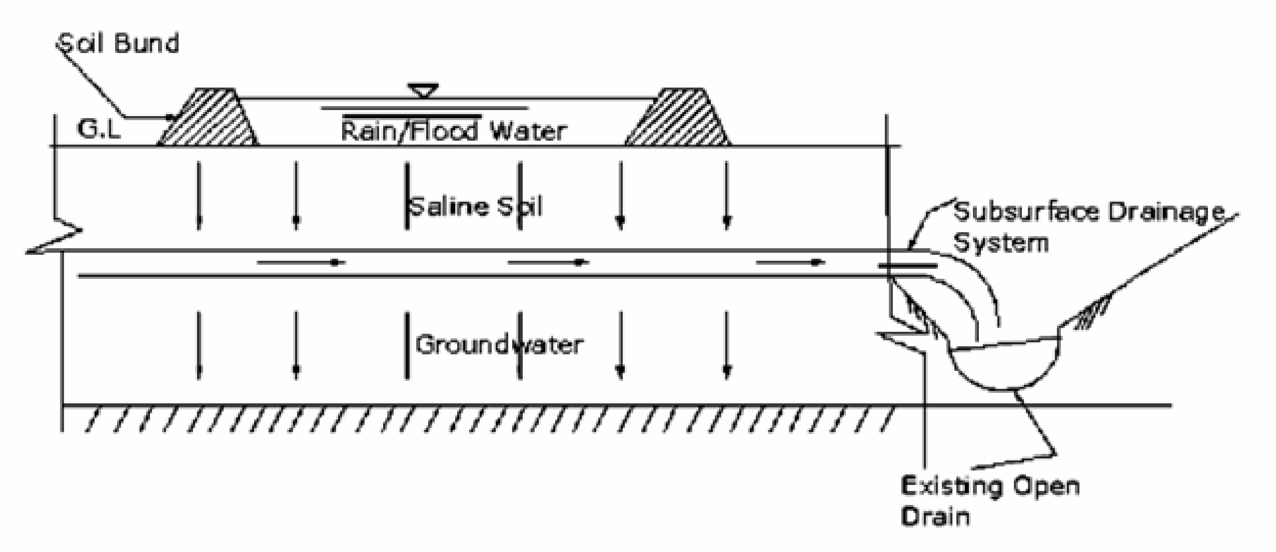


Figure 5. Leaching of Saline Soil Using Rain/Flood Water.

APPLICATION OF GEOSPATIAL TECHNOLOGIES

Geospatial Technologies

The commonly used geospatial technologies are :

1. Remote sensing
2. Geographical Information System (GIS)
3. Global Positioning System (GPS)

Remote sensing is the art and science in which the information about any region is obtained through the data collected by various satellites or aerial photography. The remotely sensed data are available for various satellites, in different bands, at different times and at desired scales. Digital image processing makes the data more useful for applications. Geographical information system is the tool for analysis of remotely sensed and other data for variety of applications. Many programs are available for GIS with different capabilities. Global positioning system is a navigation system, which works with signals received by a receiver from satellites. Different types of receivers are available for variety of purposes.

Uses of Geospatial Technologies

Above technologies are very much useful for the planning of water resources engineering projects. Satellite image of the study area obtained through remote sensing can be used for the effective study of the area. Multi spectral, multi temporal and multi stage images are very useful for extracting the required information about the study area. GPS technology is useful for fixing the location of the points, lines, area and important features. It is also useful for preparing the digital elevation model (DEM) of the study area. GIS is useful for analysis of the area using software by overlay operations. Some of the applications of the above technologies for sustainable irrigation and reclamation of saline soil can be summarized as under :

1. Delineation of the study area
2. Fixation of watershed boundaries
3. Determination of area of the region
4. Determination of area of submergence during floods
5. Preparation of DEM of the area
6. Demarcation of crop fields, rivers, drains etc.
7. Study of direction of flow of runoff
8. Planning of overland flow directions
9. Planning for diversion of floodwater
10. Fixation of position of rivers, drains, canals, ocean etc.
11. Determination of positions of existing groundwater wells
12. Fixation of location of groundwater recharge wells

Methodology for Sustainable Irrigation

Following steps are required to be carried out for sustainable irrigation and reclamation of saline soil using geospatial technologies :

1. Determination of the study area based on need and other factors
2. Data collection about soil and crop in the study area
3. Collection of hydrological data like rainfall, flood, surface water, ground water about the study area
4. Collection and study of remotely sensed data and other maps of the study area
5. Preparation of digital elevation model or contour plan of the study area
6. Demarcation of rivers, canals, drains, saline area
7. Analysis of the data using appropriate software
8. Determination of depth of leaching required
9. Drawing the lines showing flow directions during flood and heavy rainfall
10. Determination of location of groundwater recharge wells
11. Preparation of final strategic map

CASE STUDY OF SURAT (INDIA)

A research project has been undertaken for application of geospatial technologies for sustainable irrigation, artificial recharge of ground water and reclamation of saline soil. The study area is considered near Surat city in India. Some aspects of the study are given here for highlighting the applications of geospatial technologies for sustainable irrigation and reclamation of saline soil. The study area is situated at the tail end of river Tapi as shown in Figure 6. It is a coastal area situated near Arabian Sea with the problems of seawater intrusion in aquifers and occurrence of saline soil. The rainfall is occurring during the months of June to October in the study area as well as in the catchment area of the river. River Tapi is carrying heavy floodwater generally

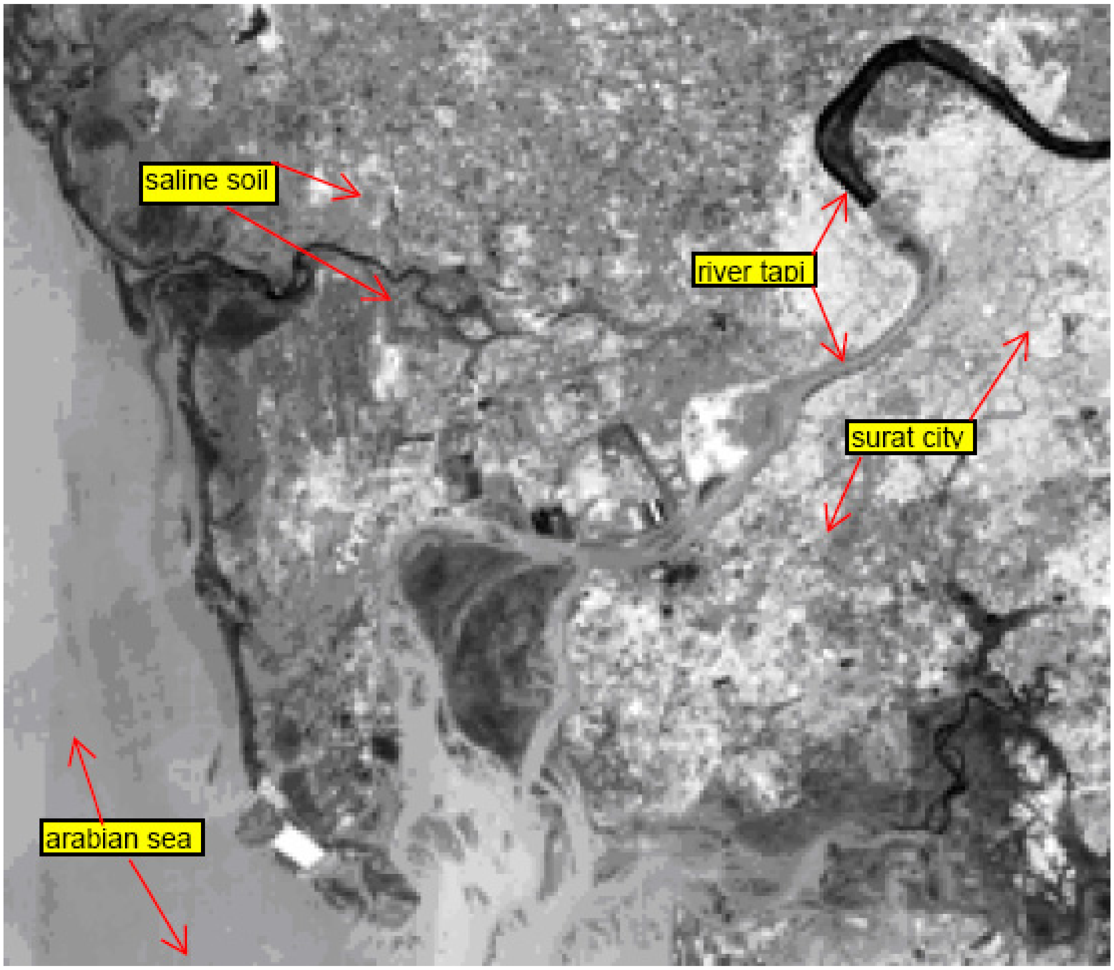


Figure 6. Study Area

during the months of August and September due to heavy rainfall on the catchment area. The tide water also enters in the tail reaches of river on certain days depending upon the tidal cycle. Due to flood in the river during monsoon season, the major portion of floodwater spreads in the Surat city and some portion on the fields in the study area. Plan has been prepared for diverting major portion the floodwater in the study area i.e. on the saline soil lands for the following purposes.

1. Reduction of flood effect in city area
2. Artificial recharge of groundwater
3. Leaching for reclamation of saline soil

The geospatial technologies i.e. satellite images, GPS receivers and software and GIS software have been used in preparing the flood diversion plan to serve above purposes. Plan for diversion of rainwater and floodwater on overland in the study area will reduce the effect of flood in residential and industrial areas. It is proposed to use a part of the diverted water for artificial recharge of ground water in the study area through numbers of existing as well as newly constructed recharge wells, which will also be useful to improve the quality of ground water and control of seawater intrusion. It is also proposed to construct artificial ground water recharge wells in conjunction with storm water drainage systems at some parts of the area under considerations. The major part of the diverted flood water is to be utilized for leaching purpose, which will be useful for reclamation of saline soil in the region.

CONCLUSION

Sustainable irrigation is possible by adopting certain measures. Storage of water underground through artificial recharge of ground water using rain water and flood water is one of the measures. Reclamation of saline soil is another measure, which is possible by leaching of the agricultural fields using rain water or flood water. There are multi advantages in both of the activities. Geospatial technologies like remote sensing, GIS and GPS are very useful for planning of both the activities. A case study of Surat (India) is also discussed in the paper for highlighting the application of geospatial technologies for sustainable irrigation and reclamation of saline soil.

REFERENCES

Dvoracek M. J. and Peterson S.H., 1971, Artificial Recharge in Water Resources Management. Journal of Irrigation and Drainage Division, A.S.C.E., Vol. 97, No. IR2.

Huisman L. and Olsthoorn T.N., 1983, Artificial Groundwater Recharge, 1st edition, Pitman Advanced Publishing Program, London.

Patel J.N. and Gotawala H.C., 2001, Some Aspects of Storm water Drainage System in Conjunction with Groundwater Recharge, International conference on Civil Engineering, July 23-25, 2001, organized by Indian Institute of Science, Bangalore, India.

Patel J.N., 2002, Flood Management over a Region of River Tapi using GPS, Journal of Geospatial Today, Vol. 1, Issue 4, October-November 2002

Patel J.N., 2005, Strategy for Improvement of Groundwater Quality : A Case Study of Surat City, HYDRO - 2005, December 8-9, 2005, organized by Indian Society for Hydraulics and Siddaganga Institute of Technology, Tumkur, India.

Patel J.N., 2006, Strategy for Improvement of Groundwater Quality in the Coastal Area near a River, 2nd International Conference on Hydrology and Watershed Management, 5-8 December, 2006, Organized by J.N.T. University, Hyderabad, India.

Todd D.K., Groundwater Hydrology, 1980, 2nd edition, John Wiley & Sons, New York.

Vyas J.C., Shah N.C. and Patel J.N., 1997, Artificial Groundwater Recharge - An Important Tool for Planning in the 21st Century, International Conference on Planning for 21st Century, October 2-4, 1997, organized by University of Roorkee, India.

SOIL SALINITY DISTRIBUTIONS IN DRIP IRRIGATED VINEYARDS OF SOUTHEASTERN AUSTRALIA

Evan W. Christen[1]
Sheila DeLange[2]
Tony Patti[3]
John Hornbuckle[4]

In the Murrumbidgee Irrigation Area (MIA), in southeastern Australia there is concern that salts may be accumulating in soils under drip irrigation. This paper describes the assessment of the sustainability of drip irrigation in various vineyards after 4 to 11 years of implementing drip irrigation. A total of six drip irrigated vineyards were sampled in the row and inter row for soil salinity. Four of the six sites were chosen because there was historical soil salinity data associated with them from before drip irrigation was implemented. This historical data was used for comparison with current soil salinity data. At all vineyards it was found that salt concentrations in the rootzone were below vine tolerance thresholds of 1.5 dS/m. The results also showed that the salt concentrations in soils under drip irrigation actually tended to decrease with time, especially in the inter row that was no longer watered. There were large variations in the distributions of salinity within vineyards and between vineyards. The salinity profiles were highly varied. It would appear that there is little danger of salt accumulation in the rootzone in this context, probably due to the low salinity irrigation water and the potential for leaching by rainfall.

INTRODUCTION

In most perennial horticultural irrigation regions world-wide there is a transition from flood/furrow irrigation to drip-irrigation. This is also true for the Murrumbidgee Irrigation Area in south-eastern Australia. Although this transition has been ongoing for some decades, there is now added impetus by recent initiatives to implement high tech irrigation systems in return for their water savings, which can be used for environmental purposes. Changing over to 'high tech' irrigation is a strategy used by farmers to aid them in achieving higher water use efficiency, higher quality crop production and reducing environmental impacts such as surface runoff and deep percolation (Hanson, et al. 1997).

As farmers across the Murrumbidgee Irrigation Area strive to use less water and increase their water use efficiency by implementing drip irrigation systems, there is growing concern that salts may be accumulating in these soils. In arid zones of California there is recent evidence that salts are accumulating in the soils of orchards with drip irrigation (Burt and Isbell, 2003). Salt accumulation under drip irrigation has also been documented in other semi-arid to arid regions of

[1]Senior Research Scientist, CSIRO Land and Water, Griffith, NSW, 2680, Australia & Adj. Assoc. Prof. University of New England & Project Leader Co-operative Research Center for Irrigation Futures; evan.christen@csiro.au
[2]Honours student, Monash University, Melbourne, Australia
[3]Research Scientist, Monash University, Melbourne, Australia
[4]Research Scientist, CSIRO Land and Water, Griffith, NSW, 2680, Australia & Co-operative Research Center for Irrigation Futures

the world, namely Israel, Egypt and Saudi Arabia (Rawitz, 1983; Nimah, 1985 and Abd El – Razek, et al. 1992).

The foreseeable problem of salt accumulation in soils under drip irrigation is the potential for these salts to enter into the root zone of plants and accumulate due to the low water application rates. These salts can have detrimental affects on crop growth, especially perennial horticultural crops such as grapevines which remain planted in one area for a long time. Maas and Hoffman (1977) found that grapevines are moderately sensitive to salinity, threshold of 1.5 dS/m for yield loss, up to 10% yield loss when the electrical conductivity of a saturated soil paste extract (ECe) is 2.5 dS/m or above (Stevens, et al. 1999).

METHODS

Sampling Locations

A total of six drip irrigated vineyards in the Murrumbidgee Irrigation Area of south-eastern Australia were sampled during the month of July 2004. Vineyards chosen were those that had been using drip irrigation for between 9 and 11 years, and one for 4 years. Previously these vineyards had been furrow or flood irrigated. It was assumed that the vineyards using drip irrigation for 9 years and more would have had enough time to develop a soil salinity distribution that reflected the water application using drip irrigation. The vineyard with 4 years of drip irrigation was chosen as one that would be partially toward developing a salt distribution that reflected the drip irrigation. Table 1, describes the characteristics of the vineyards. Three of the six vineyards (numbers 2, 3 and 4) were also chosen because there was historical soil salinity data associated with them. This historical data was then used for comparison with current soil salinity data.

The Murrumbidgee Irrigation Area (MIA) of New South Wales, Australia lies at latitude 34^0 S and longitude 146^0 E. The MIA climate is described as 'Mediterranean' or semi-arid. The summers are hot and dry, winters are mild with frosty nights. Mean annual rainfall is 418 mm which is fairly evenly distributed throughout the year. Mean annual potential evapotranspiration (ETo) is 1800 mm and rainfall is highly variable ranging from 140 to 700 mm annually. Only during the winter months does mean rainfall almost match ETo. Irrigation water is supplied from the Murrumbidgee River which has very low salt concentrations. The electrical conductivity of irrigation water from this source varies between 0.05 to 0.15 dS/m.

Table 1. General information on the six sites sampled for soil salinity.

Farm No.	1	2	3	4	5	6
Soil type	Loam	Clay Loam	Clay Loam	Medium clay	Loam	Loam
Drip Irrigation (years)	10	9	4	10	10	11
Emitter rate (L/hr)	4.6	unknown	2.7	3	2.8	3.8 & 3.75
Emitter spacing (mm)	750	600	750	750	600	600
Grape Variety	Black Shiraz	Black Shiraz	Semillon	Chardonnay	Chardonnay	Semillon & Shiraz
Subsurface drainage	Y	Y	N	N	N	N
History	Long history of horticulture with flood/furrow	Long history of horticulture with flood/furrow	Previously rice, then 2 years of furrow	Previously rice, vineyard established with drip irrigation	Previously non irrigated, vineyard established with drip irrigation	Previously rice, vineyard established with drip irrigation

Soil Sampling

At each of the 6 vineyards the farmer was asked to locate a site with normal or above average growth and a site of reduced growth, thus providing two replicates per farm and a total of 12 sites in total. At each of these sites soil samples were taken along the vine row, i.e. under the dripper line, and perpendicular to the vine row, i.e. into the inter-row area. Altogether six soil cores were collected, one underneath the drip emitter, one between the drip emitters and the other four out into the middle of the vine row, as shown in Figure 1. Each soil core went to a depth of 80 cm, as it was anticipated that the roots would not grow much deeper than that in these soil types under the drip irrigation (Cox, 1995).

Each of the 80 cm soil cores were divided into 10 cm increments from 0 – 40 cm depth and 20 cm increments from 40 cm – 80 cm depth, a total of six soil samples from each soil core. All soil samples were stored in air tight plastic bags to prevent any moisture loss.

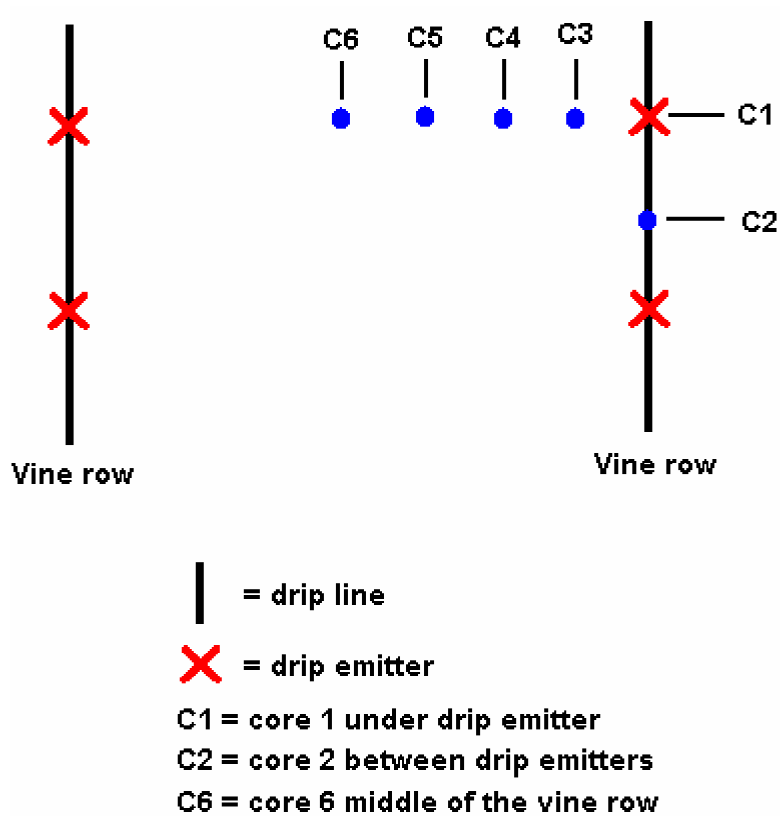


Figure 1. Soil sampling procedure. The distance from C1 to C6 the middle of the vine row was 160 cm, where cores C1 to C3, C3 to C4 and so on are at 40 cm increments.

Soil salinity measurement

Electrical conductivity was measured using the 1:5 soil/water extract method (Rayment and Higginson 1992) and values were converted to EC saturated paste (ECe) using a conversion factor of 6.1, based upon regression of the 1:5 method to saturated paste from sub samples of 12 of these soils, figure 2.

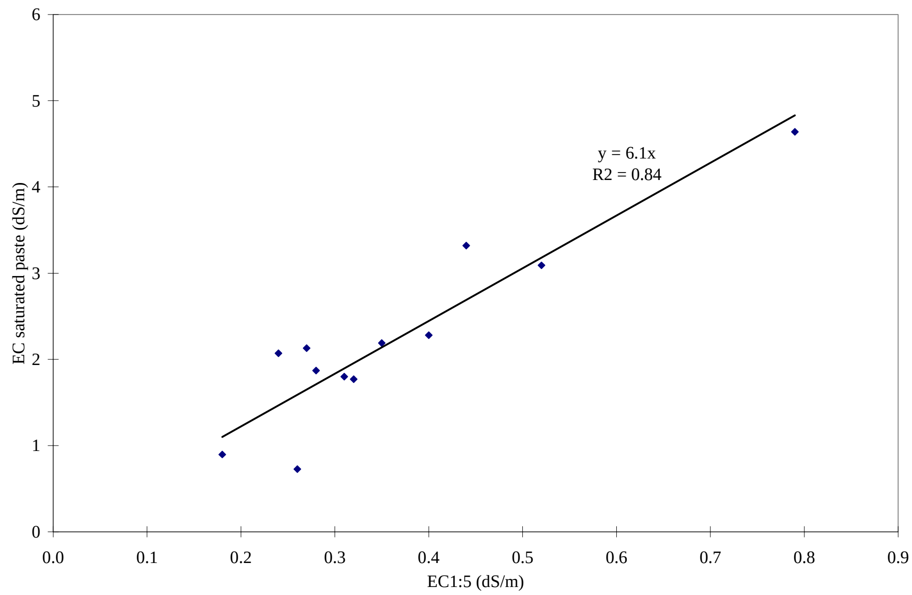


Figure 2. Soil electrical conductivity, Saturated paste v 1:5 soil:water extract

RESULTS

The soil salinity readings were plotted using the Surfer program (Golden Software) to produce a contour plot of the salinity distribution.

Soil Salinity distribution along the row

Analysis of the soil cores from under the vine row showed that 10 of the 12 sites had soil salinities less than 1.5 dS/m (the threshold for yield loss) and 11 of the 12 sites had soil salinities less than 2.5 dS/m (the threshold for 10% yield loss). Figures 3 and 4 show typical sections where the soil salinity was below the yield loss threshold. The soil salinity is low down to 80cm. There is a slight tendency of higher soil salinity halfway between emitters but the salinity is still below threshold levels. Figures 5 and 6 show the sites with the highest salinity levels. Even at these worst sites the top 70cm of soil, in figure 5, and top 40cm of soil, in figure 6, had soil salinities lower than the threshold level. The most saline site, shown in figure 6, is vineyard 3 which had only been under drip irrigation for 4 years and had been a vineyard for only 6 years, previously being used for rice. Thus, this site is unlikely to yet have come to a new equilibrium with the changed irrigation conditions.

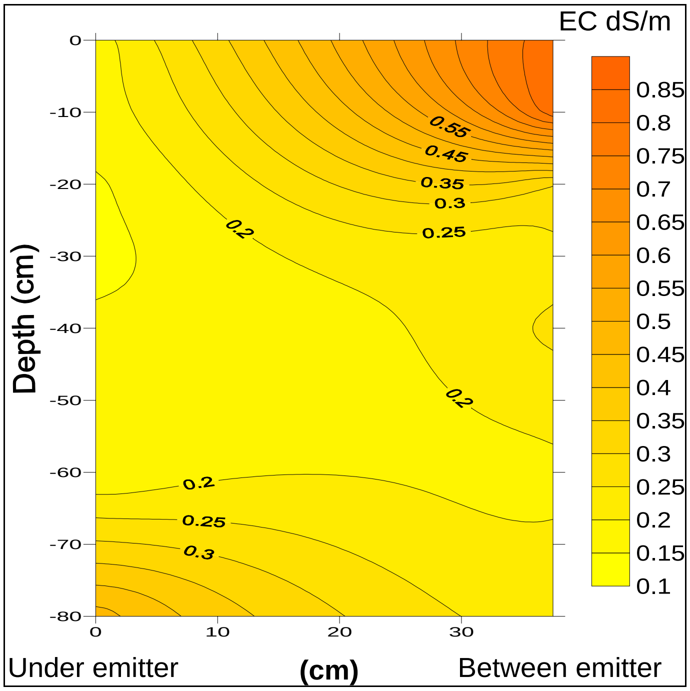


Figure 3. Typical low soil salinity (ECe) along vine (Vineyard 1)

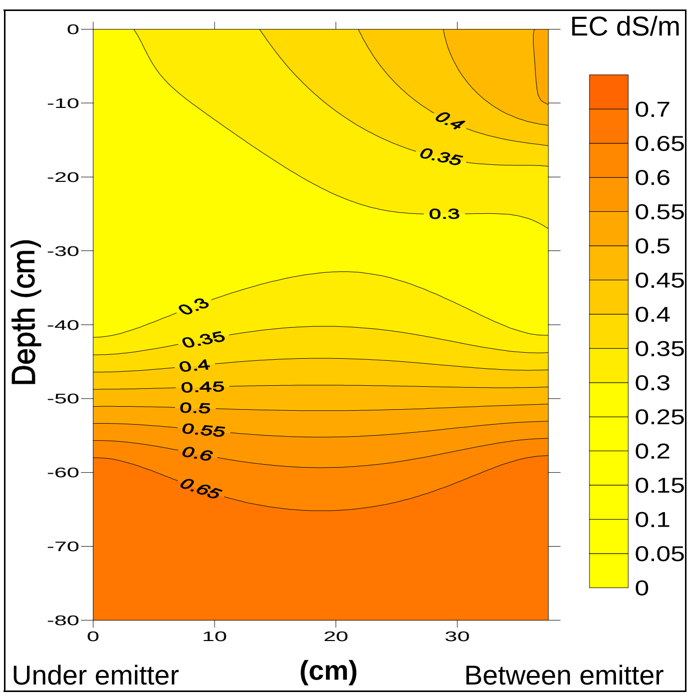


Figure 4. Typical low soil salinity (ECe) along vine (Vineyard 4)

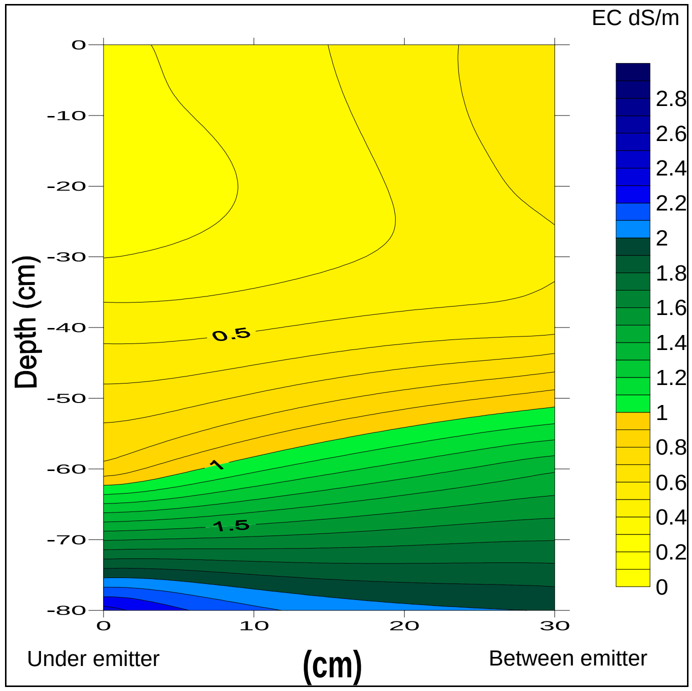


Figure 5. High soil salinity (ECe) measured along vine row (Vineyard 6)

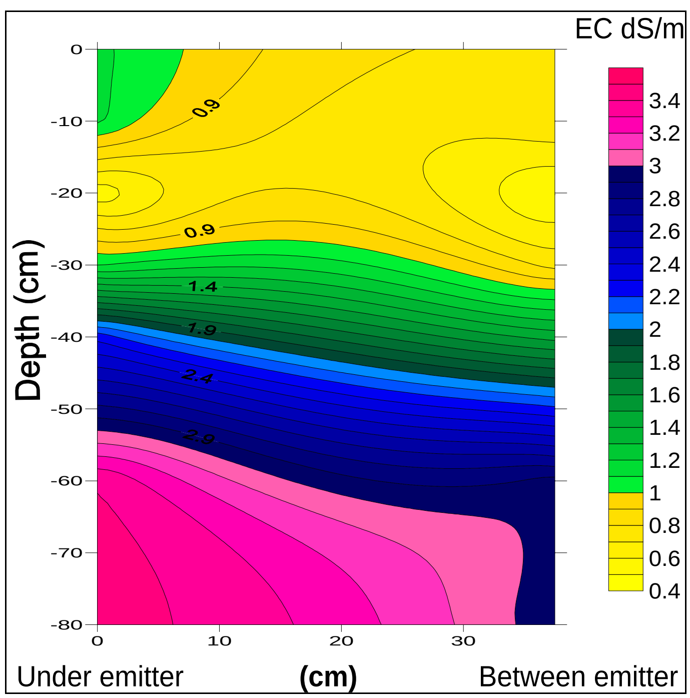


Figure 6. Highest soil salinity (ECe) measured along vine row (Vineyard 3)

Soil Salinity distribution perpendicular to the row

The soil salinity distributions perpendicular from the row were much more variable than the salinity levels and distribution along the row as shown in the previous section. Of the 12 sites, 7 showed what could be described as a uniformly low salinity across the section, an example is shown in figure 7.

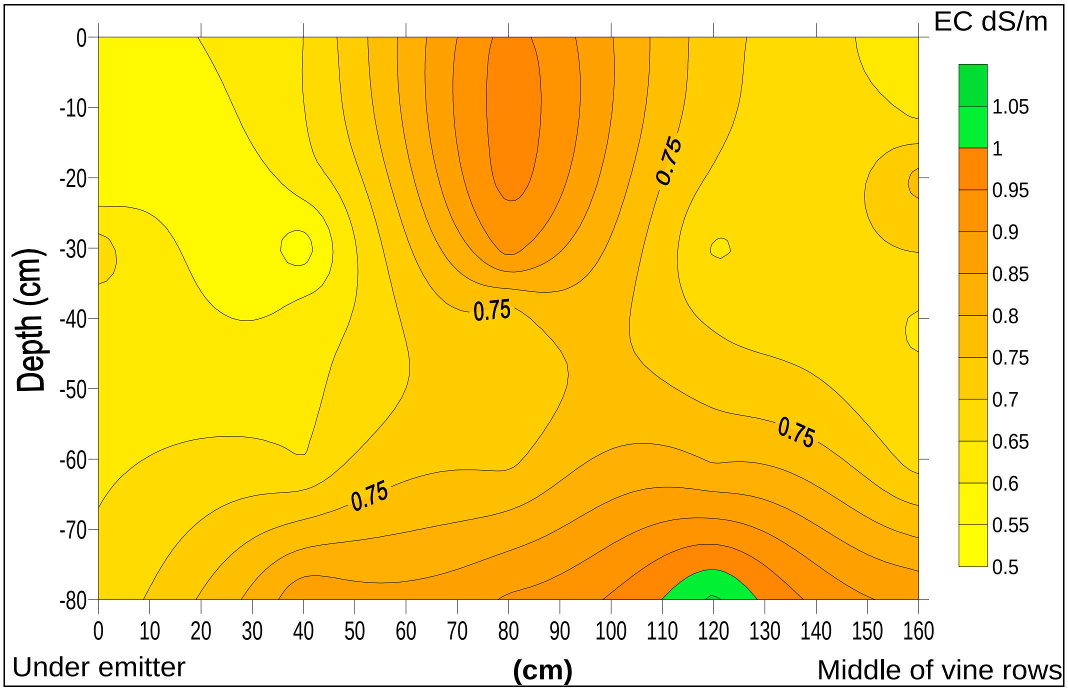


Figure 7. Uniformly low soil salinity (ECe) measured perpendicular to vine row (Vineyard 2)

Of the other sites where there were higher salinities, the zone near the drip emitter was always below the threshold level. Sometimes this zone extended to depth, at other sites there was salinity at depth. Those sites that had low salinity below the emitter to the sampled depth of 80cm were found to have increased salinity at around 60 to 100cm away from the vine row exceeding threshold levels, examples of these salt distributions are shown in figures 8 and 9.

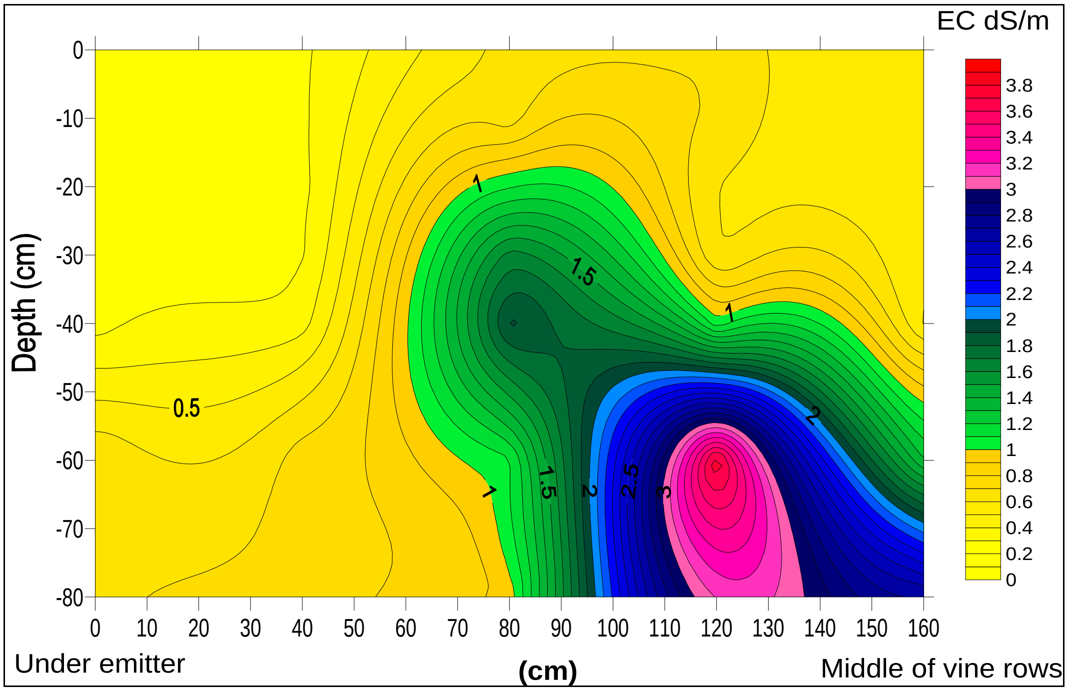


Figure 8. Under the row low soil salinity (ECe) to 80cm, but increasing soil salinity away from the vine row, (Vineyard 4).

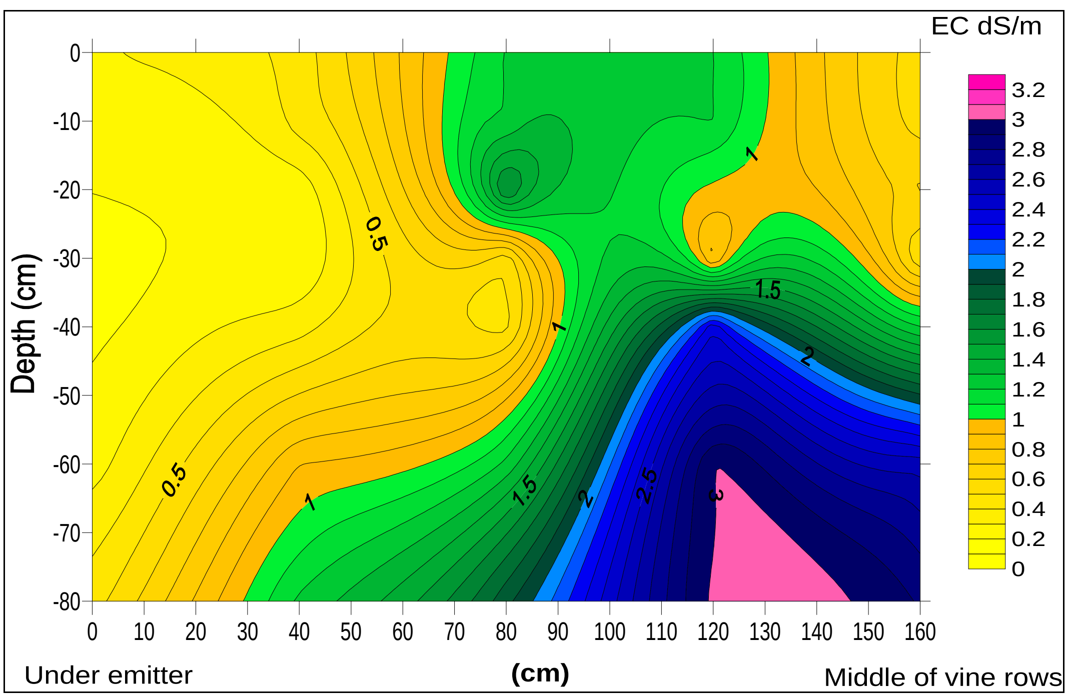


Figure 9. Under the row low soil salinity (ECe) to 80cm, but increasing soil salinity away from the vine row, (Vineyard 1).

Of the other sites where salinities were higher, there was one where the salinity appeared to increase uniformly with depth across the section, figure 10.

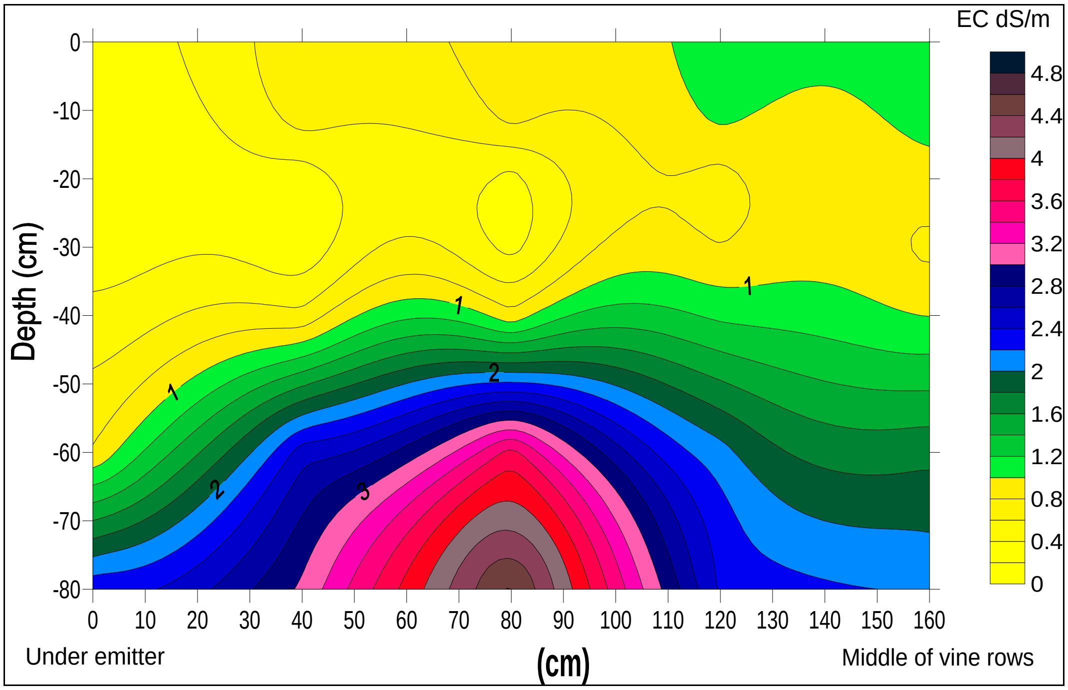


Figure 10. Increasing soil salinity (ECe) relatively uniformly with depth perpendicular to the row (Vineyard 6).

In the other high salinity sites there were three that showed only a small zone of low salinity soil around the emitter with soil salinities increasing both with depth and perpendicularly away from the row, figures 11, 12 and 13. These three sites would have the most restricted rooting area of low salinity soil.

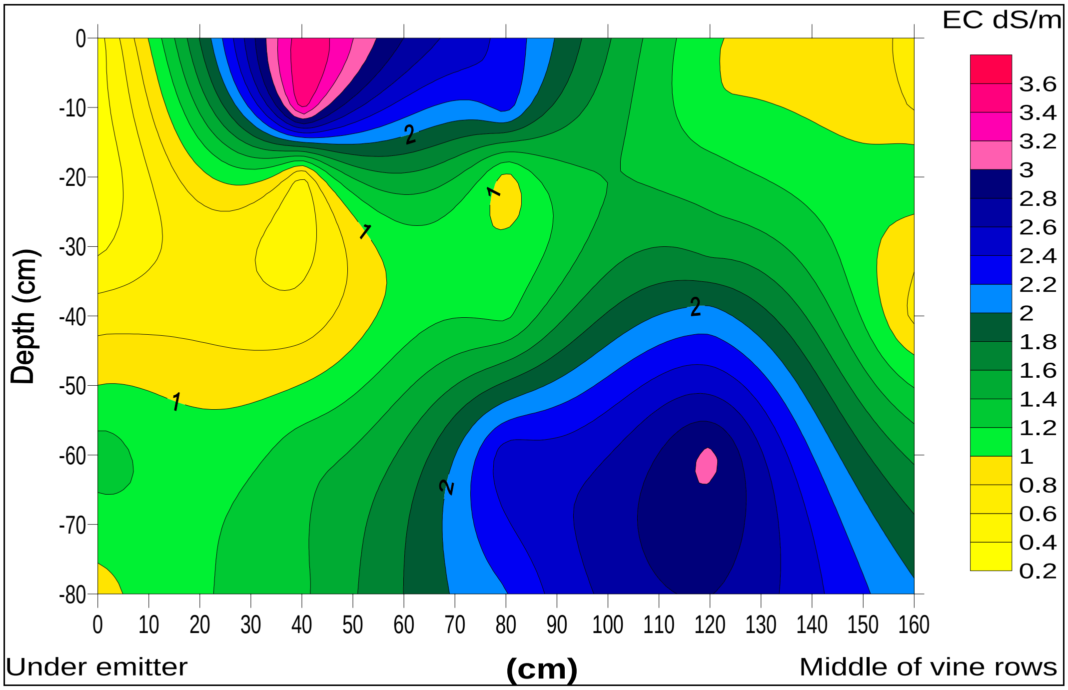


Figure 11. Increasing soil salinity (ECe) with depth, and perpendicular to the vine row (Vineyard 6).

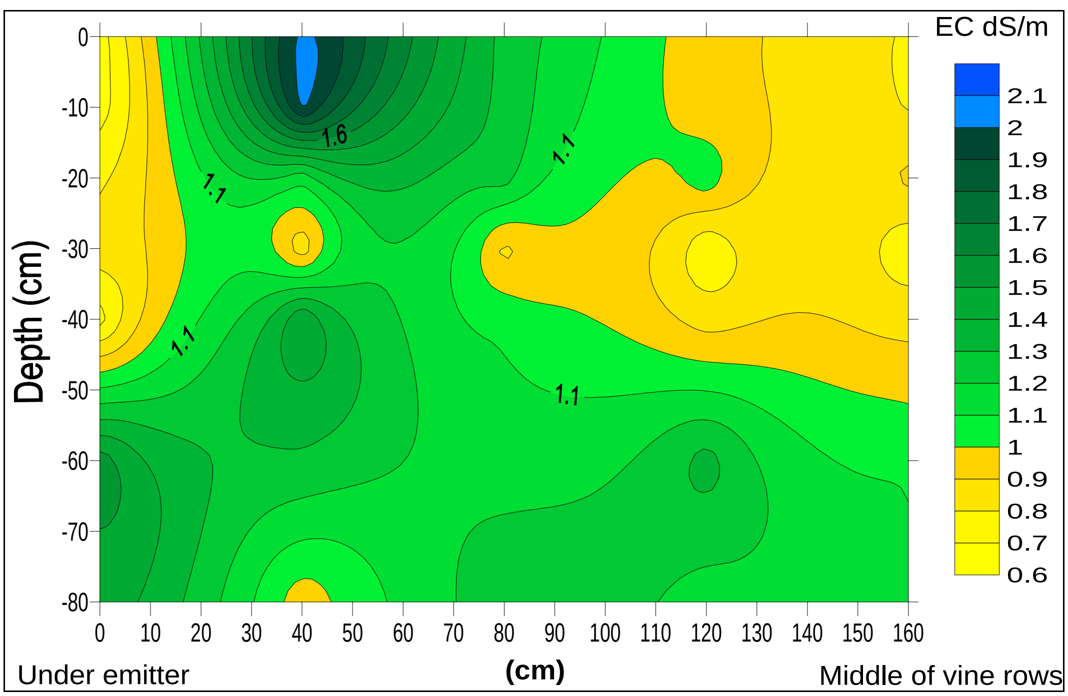


Figure 12. Increasing soil salinity (ECe) with depth, and perpendicular to the vine row (Vineyard 3).

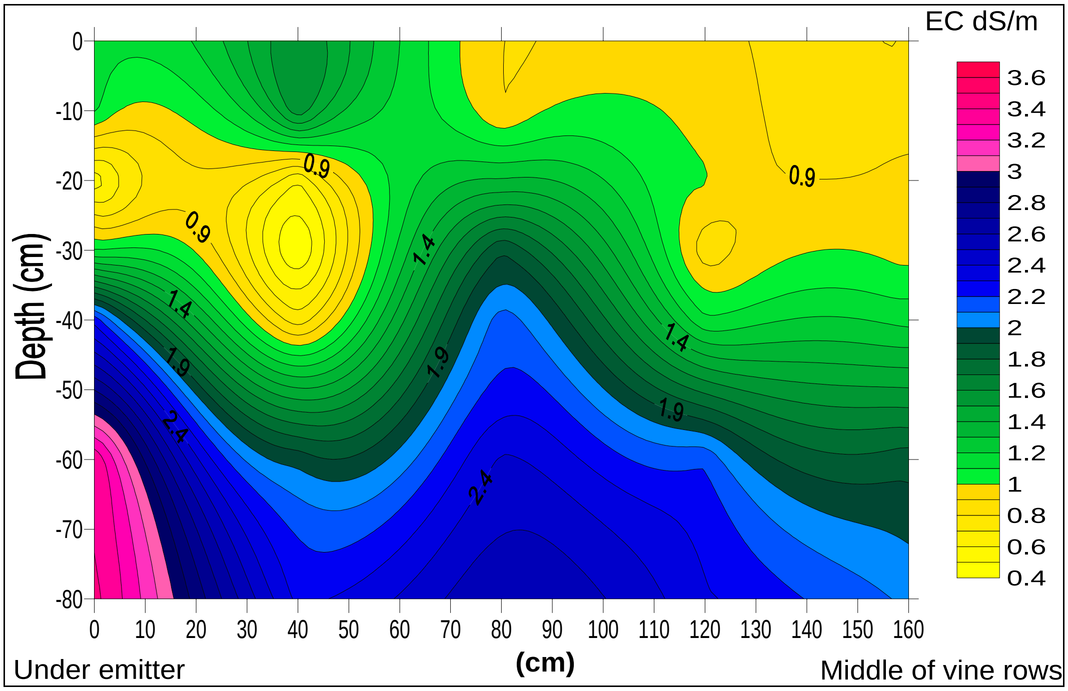


Figure 13. Increasing soil salinity (ECe) with depth, and perpendicular to the vine row (Vineyard 3).

<u>Mid row soil salinity changes over 8 years (1996 to 2004)</u>

The mid row soil sampling regime undertaken in 2004 followed that undertaken 8 years in vineyards 2, 3 and 4. A comparison of the soil salinities is shown in table 2. It can be seen that the mid row salinities have reduced dramatically over those 8 years. The soil salinity in vineyard 3 has changed less than vineyard 2 and 4 as it has only been under drip irrigation for 4 years as compared to 9 and 10 years for vineyard 2 and 4 respectively.

Table 2. Average soil salinity ECe (dS/m) in the middle of the vine rows in 1996 and 2004.

Depth (cm)	Vineyard 2			Vineyard 3			Vineyard 4		
	1996	2004	Change	1996	2004	Change	1996	2004	Change
-5	1.16	0.54	-0.62	0.88	0.8	-0.08	1.82	0.68	-1.14
-15	2.4	0.6	-1.8	0.87	0.94	+0.07	1.77	0.5	-1.27
-25	3.14	0.46	-2.68	1.32	0.84	-0.48	1.58	0.43	-1.15
-35	3.04	0.42	-2.62	1.6	1.01	-0.59	1.58	0.42	-1.16
-50	2.66	0.65	-2.01	1.91	1.47	-0.44	1.65	1.04	-0.61
-70	2.37	0.72	-1.65	1.87	1.6	-0.27	1.6	1.69	+0.09

DISCUSSION

The soil salinity at the 12 sites could be broadly classified into 8 where soil salinity is uniformly well below levels likely to affect grapevines, two with small areas of soil salinity above threshold levels and two with large areas above potential salinity levels. However, even at those most saline sites soil salinity was less than the threshold level directly under the drip emitter, at least to a depth of 50 cm and at least 25 cm away from the drip emitter into the middle of the vine rows. Hence in reality none of the vineyards are experiencing any adverse effects from soil salinity. The two sites with highest salinities had been under drip irrigation for the shortest time (4 years) and hence are probably still in a transitional phase.

The 6 vineyards were chosen because they had been using drip irrigation for at least 4 years and it was anticipated that this would minimise any affects of previous irrigations methods on salt accumulation and distribution in the soils. However, it appears that previous irrigation methods may have had an influence on the current salt distributions throughout the soil profiles. Both vineyards 1 and 2 had a long history of horticulture with flood/furrow irrigation prior to drip irrigation installation in 1994/5. At vineyard 2 the salt concentrations were below 1 dS/m throughout the soil profile and the salt concentrations at vineyard 2 increased slightly with depth and away from the drip emitter. This is in contrast to the soil salinity results found at vineyards 3 and 6, where higher salt concentrations were evident in the surface soil layers as well as at depth. Both vineyards have had a history of rice farming prior to drip irrigation installation and the higher salt concentrations and wider distributions of salts exceeding 2 dS/m may be a remnant of the previous farming practice.

The four vineyards sampled in 1995/6 showed a decrease in soil salinity in the inter-row in 2004. This decrease in soil salinity was in the range to 0.5 to 2 dS/m and occurred to the maximum sampling depth of 70cm.

This positive result of decreased soil salinity in drip-irrigated vineyards in the Murrumbidgee Irrigation Area is probably attributed to a number of factors; 1) The quality of the irrigation water in the MIA is very good, ranging from 0.05 to 0.15 dS/m. This is in contrast to other arid zone irrigation areas of the world, where the salinity of the irrigation water ranges from 0.4 – 2 dS/m (Burt and Isbell, 2003 and Tayel, et al. 1988), 2) The relatively low soil salinities in these soils prior to drip irrigation being implemented, and 3) There is sufficient rainfall, annual average 410mm for leaching to occur.

CONCLUSIONS

- Soil sampling of vineyards that had been drip irrigated for between 4 and 11 years in the Murrumbidgee Irrigation Area of southeastern Australia did not show any hazardous build up of soil salinity in the rootzone.
- Interrow salinity had decreased to the sampling depth of 70cm on 4 farms that had been sampled in 1995/96 and again in 2004. This indicates that leaching by rainfall had occurred.
- Drip irrigation with high quality water (0.05 -0.15 dS/m) in the Murrumbidgee Irrigation Area is unlikely to result in hazardous accumulations of soil salinity.

ACKNOWLEDGEMENTS

We would like to thank all the farmers participating in the survey for their assistance.

REFERENCES

Abd El – Razek, A.A., Wahdan, A.A., Kaoud, E.E. and Abd El – Shafi, A.M. (1992). Soil Moisture and Salt distribution patterns in clay soils as affected by different irrigation systems. *Egypt. J. Soil Sci.* **3:** 343-360.

Burt, C. and Isbell, B. (2003). *Soil Salinity Accumulation in Orchards with Drip and Micro-spray Irrigation in Arid Areas of California.* ITRC Report No. R 03-005. (Irrigation Training and Research Centre: California Polytechnic State University, San Luis Obispo).

Cox, S. (1995). “Soil Water Conditions and Root Distributions under Grape Vines with Drips, Riverina Twin Furrow and Flood Irrigation”, CSIRO Division of Water Resources, Project DDEA Irrigation and Drainage Management Horticulture, Vac. Stud. Rep. Nov-Mar. 1995

Hansen, B., Schwankl, L., Gratten, S. and Prichard, T. (1997). *Drip irrigation for row crops.* (Department of Land, Air and Water Resources, University of California: Davis, California).

Maas, E. V., and Hoffman, G. J. (1977). Crop salt tolerance-current assessment. *Journal of the Irrigation and Drainage Division, American Society of Civil Engineers* 103: 115-134.

Nimah, M.N. (1985). Localized trickle versus drip irrigation systems. In: *Drip/Trickle Irrigation in Action. Proceedings of the Third International Drip/Trickle Irrigation Congress,* November 18-21. (ASAE: St Joseph, Michigan, USA). pp. 552-554.

Rawitz, E. (1983). Management of Saline Soils in Israel. In: *Isotope and radiation techniques in soil physics and irrigation studies,* April 18-22 (International Atomic Energy Agency: Vienna, Austria). pp. 249-258.

Rayment, G.E. and Higginson, F.R. (1992). *Australian Laboratory Handbook of Soil and Water Chemical Methods.* (Inkata Press: Melbourne).

Stevens, R.M., Harvey, G., Partington, D.L. and Coombe, B.G. (1999). Irrigation of grapevines with saline water at different growth stages. 1. Effects on soil, vegetative growth, and yield. *Aust. J. Agric. Res.* 50: 343-355.

DRAINAGE AND IRRIGATION WATER QUALITY MANAGEMENT IN EASTERN CANADA

Professor Dr. Chandra A. Madramootoo, P.Eng.[1]

ABSTRACT

Subsurface drainage is essential for crop production in Eastern Canada. Excess precipitation from snowmelt and rainfall must be artificially removed, in order to provide an optimum soil-air-water environment in the crop root zone. In addition, to make optimum use of the limited heat units and short growing season, it is essential that soil conditions permit field machine trafficability in the Spring, for seedbed preparation and planting operations. There are close to 3 million hectares of subsurface drained land in the wet humid regions of Eastern Canada.

In recent years, there has been much concern about the water quality impacts of shallow subsurface drainage. Elevated concentrations of nitrate-nitrogen and dissolved phosphorus have been measured in tile drainage outlets. These high nutrient concentrations have led to eutrophication of rivers and lakes. The sources of these nutrients are fertilizers and manures from intensive animal production operations.

Best management practices have therefore been developed and tested to reduce the nutrient loadings from subsurface drainage systems. One of the practices which has widescale applicability is sub-irrigation. An advantage of sub-irrigation is that it uses the existing subsurface drainage system to supply crop water requirements during the summer growing season, when droughts may occur. In addition, sub-irrigation promotes denitrification, thereby reducing nitrate-nitrogen concentrations in tile drainage effluent.

This paper will describe the water quality impacts of tile drainage in Eastern Canada, and the results of our research program in reducing pollution from tile drainage systems. Best practices for improving drainage and irrigation water quality will be presented, and an analysis of the benefits will be discussed.

INTRODUCTION

The Eastern Canadian and Maritime provinces of Quebec, Ontario, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador are located in a temperate humid region where the average annual precipitation exceeds the annual evapotranspiration. This excess water hampers crop growth, and needs to be removed in order to have a competitive agricultural sector. The soils of the region have been formed from sedimentary deposits during the retreat of the glaciers, and the resultant glacial tills comprise a mixture of sands, silts and loams overlying heavy clays. These soils have low hydraulic conductivities and are imperfectly

[1] Vice President Honoraire, ICID; James McGill Professor of Irrigation and Drainage Engineering and Dean, Faculty of agricultural and Environmental Sciences, McGill University, Montreal, Canada H9X 3V9; Chandra.madramootoo@mcgill.ca

drained. Such wet soils under relatively high water table conditions require artificial drainage to support an economically viable agri-food sector.

The provinces of Quebec and Ontario have implemented large scale subsurface drainage projects, in order to remove excess soil water for sustainable crop production. The average annual precipitation from snow and rain is estimated as 1200 mm. The evaporation varies from about 400 to 500 mm. Measurements by Gollamudi and Madramootoo (2006) show that surface runoff is just over 100 mm/year and the amount of water removed by the subsurface tile drains is in excess of 400 mm/year.

The earliest subsurface drains were installed in the late 1800s, and the drains were randomly installed. The drains were made of clay tile. Surface drainage systems, comprised of lined ditches, cambered beds and open main drains were installed in conjunction with the tile lines. This type of drainage continued until the 1970s, when corrugated plastic pipe entered the market. Since then land owners and farmers have moved to a more systematic type of parallel lateral subsurface drainage system, with the lateral pips connected to plastic mains and submains. Lateral drain spacing is computed using a steady state drain spacing equation, with inputs of the design drainage rate and soil hydraulic conductivity. The subsurface drains are installed with high speed trenchless drain laying equipment, guided by laser grade control systems.

There are approximately 3 million ha of tile drained land in Quebec and Ontario, and there is potential to drain additional land areas. Random clay tile systems are being replaced by systematic plastic pipes, especially as clay tiles become clogged and broken. Closely spaced subsurface drains are also replacing open field ditches, thus making it easier for field equipment to traverse large fields. In areas with fine sands and silts, synthetic geotextiles are wrapped around the drain pipes to reduce sedimentation and blockage of the pipes.

There are however growing societal and environmental concerns about the impacts of drainage on water quality. Madramootoo et al. (1992) have pointed out that subsurface drains can be major pathways of nutrients to rivers and lakes. They found that nitrate-nitrogen concentrations from a tile drainage system on a sandy loam soil cropped to potatoes often exceeded the water quality standards of 10 mg/l. In addition, Enright and Madramootoo (2004) measured flow weighted average annual phosphorus concentrations in surface runoff ranging from 0.2 to 2.15 mg/l. The average annual P concentrations in tile drainage flow ranged from 0.06 to 0.37 mg/l. These high concentrations of N and P have led to the formation of algal blooms and cyanobacterial outbreaks in Quebec's lakes and waterways. Gollamudi and Madramootoo (2006) showed that particulate P and bioavailable P were significant forms of P in tile drainage.

Therefore, current emphasis is on developing technologies and best management practices that reduce the concentrations of nutrients in tile drainage flows and improve drainage water quality. The purpose of this paper is to examine the various techniques being used to improve drainage and irrigation water quality in Eastern Canada.

BENEFITS OF DRAINAGE AND WATER TABLE MANAGEMENT

Subsurface Drainage

The benefits of subsurface drainage can be summarized as follows:

- **i.** Better soil-air environment for root zone development and crop growth;
- **ii.** Lower water tables;
- **iii.** Improved soil structure due to better aeration of the soil profile;
- **iv.** Increased soil microbiological activity;
- **v.** Improved plant uptake of soil nutrients;
- **vi.** Reduced surface runoff, flooding and soil erosion;
- **vii.** Improved field machine trafficability;
- **viii.** Ability to implement a more diversified cropping system;
- **ix.** Ability to get on the field earlier for spring tillage and planting operations;
- **x.** Fewer restrictions to carry out timely field operations such as weed control, fertilizer applications, and harvesting;
- **xi.** Higher crop yields;
- **xii.** Increased land values.

Several researchers including Broughton (1972), have done studies to quantify the above benefits of drainage in the Ottawa-St.Lawrence lowlands of Quebec and Ontario. As a result of these studies, there has been a shift of land use from low quality forage production, to higher value crops such as corn, soybeans and vegetables. Shady (1989) pointed out that there is potential to double the drained area in Eastern Canada, if market opportunities can be identified, agricultural production intensified, and the environmental impacts due to non-point source pollution minimized.

Drainage design parameters for the Ottawa-St. Lawrence Lowlands are summarized in Box 1.

Box 1. Design drainage parameters

Drainage coefficient	10-12mm/day
Desirable water table depth	40-50 cm from the soil surface
Average drain depth	0.75-1.5m
Lateral pipe slope	>0.1% and < 2%
Lateral pipe diameter	75-100mm
Mainline diameter	100-300mm

Based on the above drainage design criteria, lateral pipe spacings range from 5 m in the fine textured heavy clay soils to about 30 m on the coarser textured sandy soils. It is important to note that often even the coarser textured sandy and sandy loam soils require drainage, since there are many pockets of layered soils, with coarser textured soils overlying finer textured and heavy clays. This impedes the percolation of snowmelt and rain water.

Various computer simulation models are used to determine the optimum drain tile depth and spacing, in order to obtain optimum crop yields. Such models include DRAINMOD (Skaggs et al., 2006) and SWACROP (Wesseling and Feddes, 2006). The advantage of such models is that they can take variable soil physical properties and soil water regimes into consideration. Studies by several researchers including Broughton (1972) and Madramootoo et al. (1995) confirm that tile drain depths ranging from 0.75 cm to 1.25 m with tile spacings of 5 to 30 m give adequate water removal and also optimum crop yields in Eastern Canada.

Water Table Management

While there is an annual excess of precipitation over evapotranspiration (ET) for the year as a whole, there are periods during the summer, when the ET is actually higher than the precipitation. This leads to periods of drought stress during the summer, and supplemental irrigation is required. The amount of supplemental irrigation required varies from 150-300 mm, depending on the year. While sprinkler and drip irrigation are used for applying supplemental water for vegetable and orchard crops, there is potential for subsurface drainage systems to be used to supply irrigation water for field crops such as grain and silage corn, soybeans, field peas, sweet corn, alfalfa, and forages. This system of combined irrigation and drainage is known as water table management, and the crops are supplied with water via upward flux or capillary rise (Evans et al., 1995).

There are two basic methods of controlling the water table, in order to help meet crop ET requirements. These are: controlled drainage (Figure 1); and subirrigation (Figure 2). With controlled drainage, the outlet on the drain mainline is restricted after the water table is lowered to meet field machine trafficability, and to provide sufficient aeration of the soil profile, to achieve suitable root development. The water table is then lowered by evapotranspiration and seepage. It could be that during a very hot dry season, the water table drops at or below the drain lines, thus limiting the upward flux or capillary rise. Crop growth and yield are therefore affected. The only way that the water table rises is through rainfall, and the rise is dependent on the amount of rainfall and the dryness of the soil profile.

Subirrigation offers an advantage over controlled drainage in that the water table does not fluctuate as much, and it remains relatively constant. This is because water is pumped back into the drain lines during the growing season. A water source is therefore necessary for subirrigation. This source can be a groundwater well, water stored in a reservoir, or runoff collected in watercourses or a pond. Subirrigation is a very inexpensive method of irrigation, since it makes use of the existing subsurface drainage infrastructure. It is best suited to flatter fields, where land slopes are less than 0.4% and on soils with relatively high hydraulic conductivity (>0.3 m/day).

Research has shown that the optimum water table depth for best crop yields is 70 cm from the soil surface (Madramootoo et al., 1995). Mejia et al. (2000) measured corn and soybean yield increases of up to 14% and 37%, respectively, above the yields of those two crops on fields with regular free outlet drainage. In order to have a better water table distribution across the field, it is sometimes necessary to have closer spaced lateral pipes, than for the drainage case. Higher crop yields could be obtained if the water table is kept closer to the root zone, and especially in drier summer growing seasons. However, in the humid region of Eastern Canada, it is possible to experience heavy rainfalls during the growing season. These sudden rains can bring the water table too high in the root zone, for extended periods, thus causing the crop to suffer from excessive wet stresses. The consequences are stunted crop growth and reduced yields.

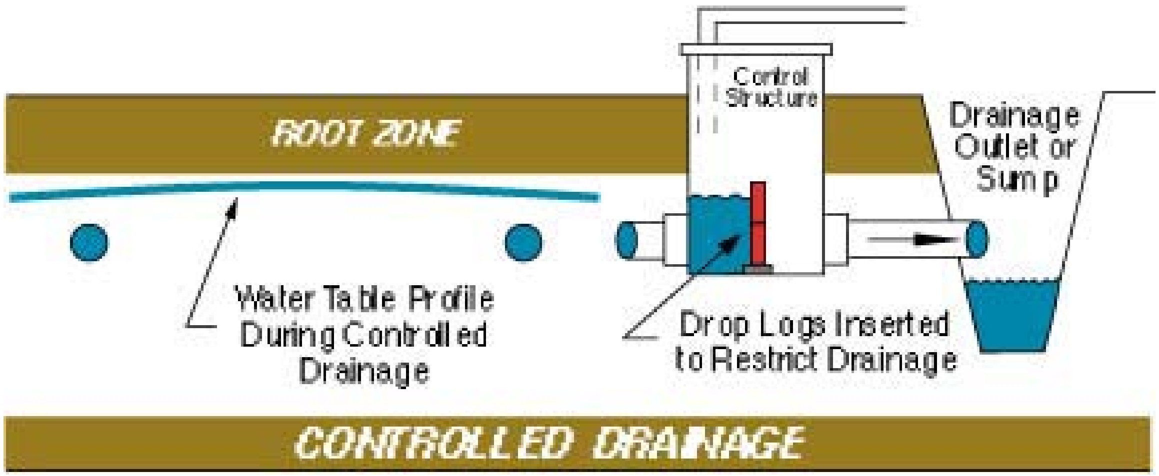


Figure 1. Schematic of controlled drainage (Zucker and Brown, 1998).

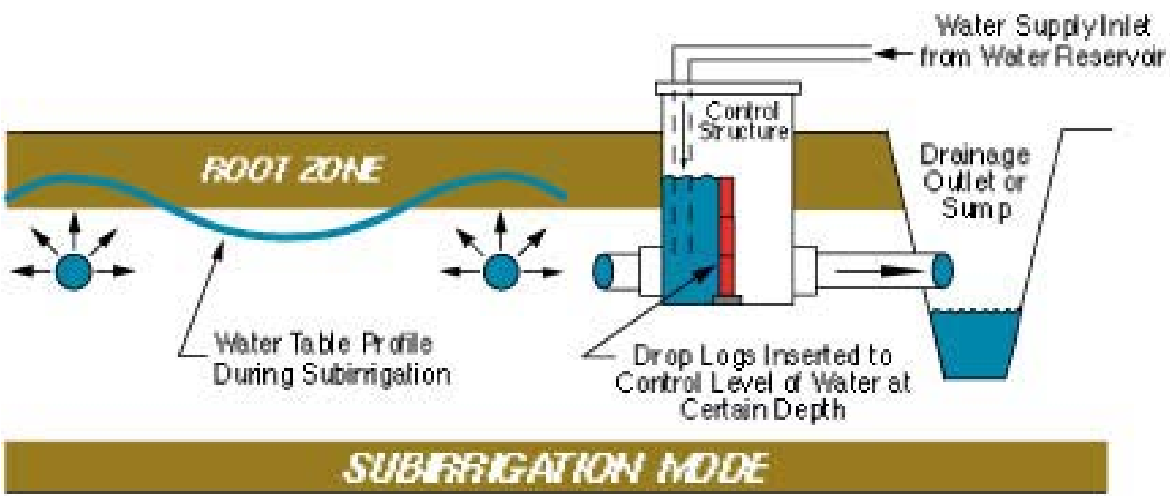


Figure 2. Schematic of subirrigation (Zucker and Brown, 1998)

WATER TABLE MANAGEMENT TO IMPROVE WATER QUALITY

In addition to the agronomic benefits of water table management, in terms of higher crop yields, there are also water quality benefits. Studies by Kaluli et al. (1999), and Mejia and Madramootoo (1998) showed that subirrigation reduces nitrate-nitrogen concentrations in drainage water by 50-60%. This translates to reductions in nitrate-nitrogen loadings of 30-94%. The reason for this improvement in water quality with subirrigation is that the higher water tables promote denitrification. The anaerobic conditions due to the higher water tables encourage the denitrifying bacteria present to convert NO3-N to two gaseous by products, nitrous oxide (N2O) and N2.

Elmi et al. (2000) conducted denitrification studies on a sandy loam soil cropped to grain corn, under different water table levels and nitrogen fertilizer rates. They found that denitrification was higher in subirrigated than conventional tile drained plots, but it was not significantly influenced by N fertilizer rate. Soil NO3-N concentrations were greater in the plots with the higher N fertilizer applications. Under subirrigation, the soil NO3-N concentrations were reduced by up to 42%. The concern is sometimes expressed that water table management may lead to increased greenhouse gas emissions, since N2O is a greenhouse gas. However, the work by Elmi et al. (2000) confirmed that the ratio of N2 to N2O emitted was much higher under subirrigation. This shows that subirrigation tends to produce a more complete conversion of the gaseous by-products of denitrification.

More recent work by Stampfli and Madramootoo (2006) has led to questions about the effects of subirrigation on phosphorus loads in tile drains. Their study showed that P concentrations in tile flow from subirrigated plots may actually be higher than those found in conventional tile drained systems. However, the reason for this might be the fact that the source of the subirrigation water might have originally had higher P concentrations. More lab and field work is being undertaken to definitively determine whether there is less reduction of P under the anaerobic conditions of water table management.

Nevertheless, based on the findings with respect to N, there is sufficient evidence that water table management (both controlled drainage and subirrigation) reduces nitrate leaching and is therefore a sound best management practice to improve water quality. One consequence is that subirrigated fields require less nitrogen fertilizer applications. The higher water tables retain the fertilizer for longer periods, thereby making the nitrogen available to the plants. This has an added economic advantage in that there is less costly requirement of fertilizer inputs.

There is potential to capture drainage effluent during the spring snowmelt period and recycle this drainage water through the drainage system for subirrigation. This is a very feasible method of water conservation and reuse. In cases where there is concern about elevated concentrations of P or other chemicals in drainage effluent, there is opportunity to treat the drainage effluent in constructed wetlands before it is returned to fresh water bodies, or reused for subirrigation.

CONCLUSIONS

Subsurface drainage is essential for crop production in Eastern Canada, due to the wet climatic conditions, poor internal soil drainage, and the topography of the region. Horizontal subsurface drainage systems lower the water table, thus improving soil machine trafficability, and improving soil productivity. Crops can be planted earlier in the spring and harvested later in the fall. Subsurface drainage in effect lengthens the growing season. Higher crop yields can thus be achieved. However, tile drains are also conduits for the movement of agro-chemicals to open water bodies. This has led to excessive N and P concentrations in rivers and lakes.

Serious environmental concerns about the impacts of drainage on water quality have led to many studies on the development of best management practices to improve drainage water quality. Water table management (WTM), comprised of both controlled drainage and subirrigation, reduces nitrate-nitrogen loads in drain flows, due to the enhanced denitrification with higher water tables. Apart from this environmental benefit of WTM, there are also agronomic and economic benefits. The higher water tables help to provide the crop ET requirements via capillary rise or upward flux. The economic benefits include the fact that less nitrogen fertilizer needs to be supplied, and the same pipe infrastructure required for drainage can be used for subirrigation. The only infrastructure difference is that there needs to be a modification to the tile drain outlet. Depending on the outlet systems chosen, the cost can vary from $500 to $2,000.

Subirrigation is restricted to fields that are relatively flat, with very few undulations, so as to achieve uniform water table conditions. On lands with slopes in excess of 0.4%, there will be a need for additional water control structures, and sources of irrigation water nearby. There are cases where it might be possible to break up fields into a series of blocks or sections, with similar topographic features, in order to achieve successful subirrigation. However, this needs to be evaluated on a case by case basis.

Other methods of improving drainage water quality include routing through constructed wetlands to remove sediment and various pollutants. The treated water can be returned directly to rivers and lakes, or reused for subirrigation. Burchell et al. (2005) have indicated that another technique for improving drainage water quality is to install shallow subsurface drainage systems. Based on some field measurements and model simulations, drains installed at 0.75m can reduce NO3-N concentrations in drainage water by as much as 16%, compared to drains installed at 1.5m depth.

It should also be emphasized that there are several other non-drainage best management practices that can improve drainage water quality. These include:

- **i.** Planting of vegetated buffer strips along ditches;
- **ii.** Improved manure storage, handling, and field disposal methods;
- **iii.** Soil nutrient testing, and implementation of nutrient management plans;
- **iv.** Timely application of nutrients and improved application techniques;
- **v.** Crop rotations and the use of perennial crops that soak up excess soil nutrients.

REFERENCES

Broughton, R.S. 1972. The performance of subsurface drainage systems on two St. Lawrence lowland soils. PhD Thesis, McGill University, Montreal, Canada.

Burchell, M.R. II, R.W. Skaggs, G.M. Chescheir, J.W. Gilliam and L.A. Arnold. 2005. Shallow subsurface drains to reduce nitrate losses from drained agricultural lands. Trans. ASAE 48(3):1079-1089.

Elmi, A., C.A. Madramootoo and C. Hamel. 2000. Influence of watertable and nitrogen management on residual soil NO_3 and denitrification rate under corn production in sandy loam soil in Quebec. Agriculture, Ecosystems and Environment, 79: 187-197.

Enright, P. and C. A. Madramootoo. 2004. Phosphorus losses in surface runoff and subsurface drainage waters on two agricultural fields in Quebec. Proc. 8th International Drainage Symposium, p. 160-170, ASAE, St. Joseph, MI.

Evans, R.O., J.W. Gilliam and R.W. Skaggs. 1995. Controlled versus conventional drainage effects on water quality. J. Irr. & Drain. Div. ASCE. 121(4):271-276.

Gollamudi, A. and C.A. Madramootoo. 2006. Water quality on surface and subsurface drained fields in Quebec - A comparative study. Presented at the Annual Conference of the Canadian Society for Bioengineering, July 16-19, 2006, Edmonton, Alberta.

Kaluli, W.J., C.A. Madramootoo, X. Zhou, A.F. Mackenzie and D.L. Smith. 1999. Subirrigation systems to minimize nitrate leaching. Journal of Irrigation and Drainage Engineering, ASCE, 125(2):52-58.

Madramootoo, C.A., Wiyo, K.A.W., and P. Enright. 1992. Nutrient losses through tile drains from two potato fields. Applied Engineering in Agriculture, 8(5):639-646.

Madramootoo, C.A., S.R. Broughton and G.T. Dodds. 1995. Water table management strategies for soybean production on a sandy loam soil in southwestern Quebec. Canadian Agricultural Engineering, 37(1):1-7.

Madramootoo, C.A., J.W. Kaluli and G.T. Dodds. 1999. Simulating nitrogen dynamics under water table management systems with DRAINMOD-N. Transactions of the American Society of Agricultural Engineers, 42(4): 965-973.

Mejia, M.N., C.A. Madramootoo and R.S. Broughton. 2000. Influence of watertable management on corn and soybean yields. Agricultural Water Management, 46: 73-89.

Mejia, M.N., and C.A. Madramootoo. 1998. Improved water quality with water table management. Journal of Irrigation and Drainage Engineering, ASCE, 124(2): 166-122.

Shady, A. M. 1989. Irrigation, Drainage and Flood Control in Canada. CIDA, Hull, QC, K1A 0G4

Skaggs, R.W., M.A. Youssef and G.M. Chescheir. 2006. Drainage design coefficients for eastern United States. Agricultural Water Management, 86(1):40-49.

Stampfli, N. and C.A. Madramootoo. 2006. Dissolved phosphorous losses in tile drainage under subirrigation. Water Quality Research Journal of Canada, 41(1):63-71.

Wesseling, J.G. and R. A. Feddes. 2006. Assessing crop water productivity from field to regional scale. Agricultural Water Management, 86(1):30-39.

Zucker, L.A. and L.C. Brown (Eds.). 1998. Agricultural Drainage: Water Quality Impacts and Subsurface Drainage Studies in the Midwest. Ohio State University Extension Bulletin 871. The Ohio State University, Columbus, Ohio 43210.

ECOLOGICAL RISK ASSESSMENT FOR SELENIUM IN THE EVALUATION OF RESTORATION ALTERNATIVES FOR SALTON SEA, CALIFORNIA

H.M. Ohlendorf[1] T.S. Pulley[2]
B.E. Sample[3] S.P. Long[4]
E.R. Byron[5] K.J. Nielsen[6]

ABSTRACT

Selenium (Se) is a chemical of ecological concern at the Salton Sea because it occurs at elevated concentrations in water, sediment, and biota of this terminal lake in southern California. Most Se in the Salton Sea enters through flows from the Alamo, New, and Whitewater rivers or in flows from agricultural drains discharging directly to the Sea. The State of California is required to evaluate alternatives for restoration of long-term stable aquatic and shoreline habitats for the historic levels and diversity of fish and wildlife that depend on the Salton Sea and for protection of water quality. Ecological risks associated with Se were evaluated under eight restoration alternatives (as well as current conditions and no action) in a programmatic-level environmental impact report. Varying types and configurations of marine, estuarine, freshwater, and terrestrial habitats would exist under the different alternatives. Ecological risks were associated primarily with existing and future Se concentrations in sediment and inflow waters. In addition to completing an ecological risk assessment for each of the habitat types in each of the alternatives, we developed an approach for ranking risk among alternatives based on the combination of habitats, representative receptors evaluated, and area of each habitat. Results of the ranking enable a comparison of alternatives with respect to their expected Se-associated risks for fish and aquatic birds (the main receptors of concern) and facilitate a maximization of habitat creation while minimizing Se exposure and risk.

INTRODUCTION

Selenium (Se) is a chemical of ecological concern at the Salton Sea because it occurs at elevated concentrations in water, sediment, and biota (California Resources Agency 2007). The State of California is required to evaluate alternatives for restoration of long-term stable aquatic and shoreline habitats for the historic levels and diversity of fish and wildlife that depend on the Salton Sea and for protection of water quality (Salton Sea Restoration Act (SB 277, Chapter 611; Fish and Game Code Chapter 13, Section 2931(c)). To evaluate the

---

[1] Environmental Scientist; CH2M HILL, 2485 Natomas Park Drive, Suite 600, Sacramento, CA 95833; harry.ohlendorf@ch2m.com
[2] Environmental Scientist; CH2M HILL, 2485 Natomas Park Drive, Suite 600, Sacramento, CA 95833; trudy.pulley@ch2m.com
[3] Environmental Scientist; CH2M HILL, 2485 Natomas Park Drive, Suite 600, Sacramento, CA 95833; brad.sample@ch2m.com
[4] Environmental Scientist; CH2M HILL, 2485 Natomas Park Drive, Suite 600, Sacramento, CA 95833; steve.long@ch2m.com
[5] Environmental Scientist; CH2M HILL, 2485 Natomas Park Drive, Suite 600, Sacramento, CA 95833; earl.byron@ch2m.com
[6] Environmental Scientist; CH2M HILL, 2485 Natomas Park Drive, Suite 600, Sacramento, CA 95833; kelly.nielsen@ch2m.com

ecological significance of Se in the various alternatives for restoration of the Salton Sea, we completed an ecological risk assessment (EcoRA) for aquatic and terrestrial receptors potentially exposed to Se in the vicinity of the Salton Sea under the potential exposure scenarios evaluated for the Programmatic Environmental Impact Report (PEIR) (California Resources Agency 2007). The EcoRA evaluated Existing Conditions, the No Action Alternative that incorporates changes reasonably expected to occur during 75 years (2003 to 2078) if other alternatives are not implemented, and eight restoration alternatives. The restoration alternatives evaluated had either passed a fatal flaw analysis or were proposed by outside stakeholders with adequate supporting information to permit analysis.

For the EcoRA, the ecological restoration goal as related to Se is to maintain sediment and water quality, food sources, and habitat conditions capable of supporting fish and wildlife (including special-status species) that are likely to be found in the study area. This paper provides an overview of the process for conducting that ecological risk assessment (EcoRA), the risk conclusions, and risk management recommendations.

APPROACH

To complete the EcoRA, we identified potential habitats for each exposure scenario and developed a conceptual model (including representative species and food webs) for each habitat; selected assessment endpoints and measures; compiled abiotic and biotic Se data into an electronic database; estimated potential future Se concentrations in sediment, soil, and surface water based on modeling of potential future Se mass loading/inflows into each habitat for each alternative; estimated potential future Se concentrations in biota based on biota-sediment accumulation factors or regression relationships derived from tissue samples collected from the Salton Sea in recent years; and characterized potential ecological exposure and risks from Se (independent of other water quality parameters).

STUDY AREA AND ECOLOGICAL SETTING

The study area included the entire Salton Sea watershed (8,360 sq. mi.), with emphasis on Salton Sea itself, its estuaries (associated with river deltas) where mixing of fresh water inflows and saline lake water occurs, freshwater marshes near the Sea, and agricultural lands that contribute drainage to the Salton Sea (Figure 1). Salton Sea is a terminal lake (i.e., has no drainage outlet), and is the largest lake in California (~365 sq. mi.); water surface elevation is about 228 ft below mean sea level (msl), and greatest water depth is about 50 ft. Salts carried by inflows have caused surface water salinity to steadily increase to its current levels of about 48 parts per thousand, which is about 1.5 times that of the ocean. This increase in salinity is expected to continue and has already resulted in changing aquatic invertebrate, fish, and bird communities based on their relative salt tolerance.

Influent riverine total Se concentrations to the Salton Sea are commonly 5 to 10 µg/L; upon reaching the Sea, the waterborne Se concentration is rapidly reduced to < 2 µg/L. Salton Sea waterborne Se appears to be rapidly assimilated into biota and settles to the bottom as part of the organically rich sediment, particularly in the deepest portions of the Salton Sea. The frequently-anoxic character of deep sediments in the Sea acts to sequester most of the Salton Sea's Se as biologically unavailable.

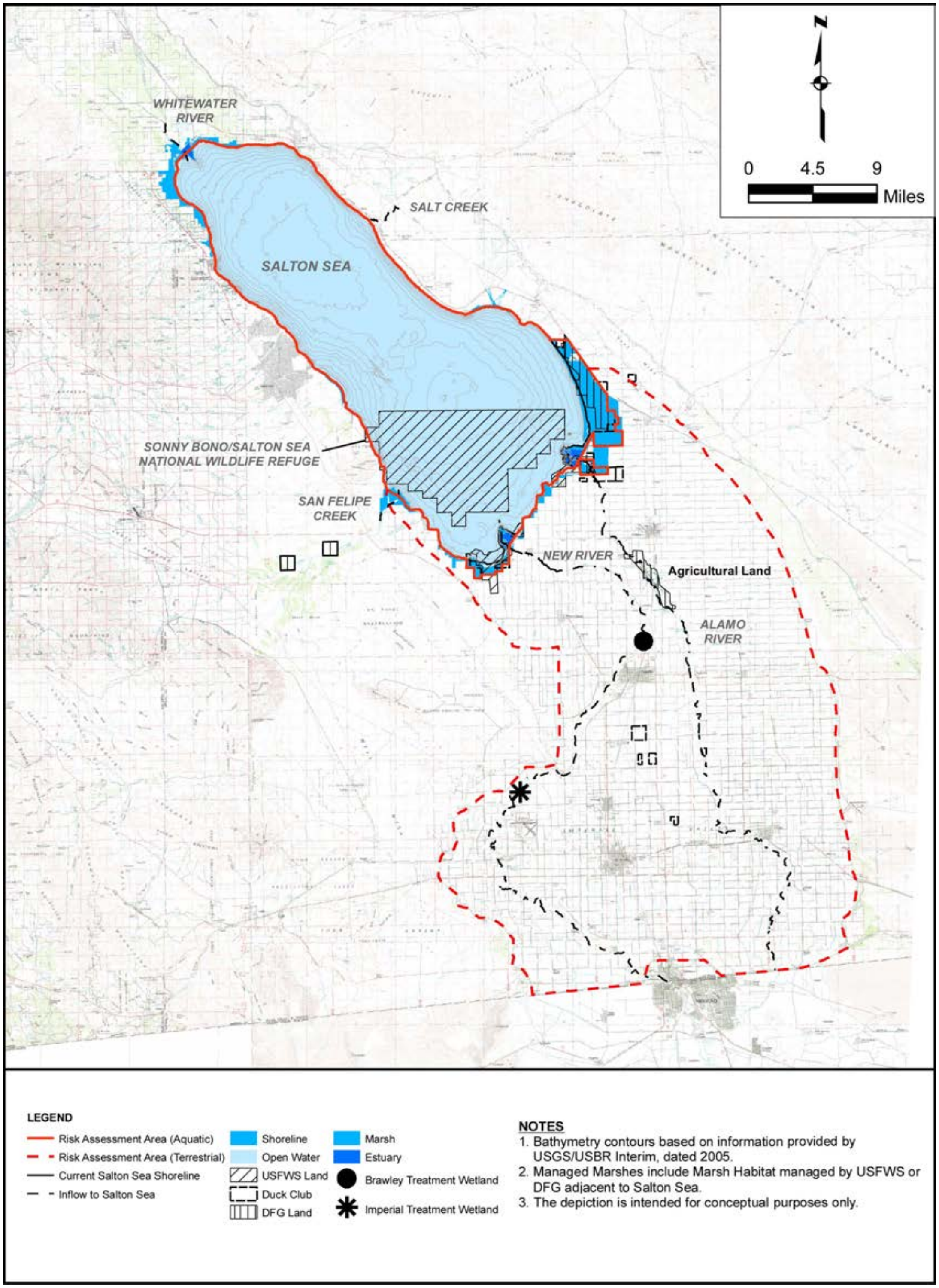


Figure 1. Salton Sea Ecological Risk Assessment Area

Current or future habitats of the Salton Sea study area include the following:

- Salton Sea “Open Water” (depth greater than 3 ft) and “Shoreline and Shallow Water” habitats (depth less than 3 ft) (Figure 2). Under existing conditions, the 95% upper confidence limit on the arithmetic mean (95 UCL) Se concentrations in sediment range from 2.32 mg/kg in the “Open Water” habitat to 1.59 mg/kg in the “Shoreline and Shallow Water” habitat.

- “Estuary” at river mouths within the Sea. Under existing conditions, the 95 UCL Se concentrations in sediment range from 0.43 mg/kg to 1.93 mg/kg in the “Estuary” habitats associated with the three influent rivers.

- “Marine Sea” (future habitat similar to existing Salton Sea’s combined Open Water and Shoreline and Shallow Water habitats)

- “Saline Habitat Complex” (future habitat that may be formed under several restoration alternatives; it would contain saline waters up to ~10 ft deep to provide habitat similar to Shoreline and Shallow Water habitat)

- “Lakes and Rings” (not currently present, but would be formed in two alternatives)

- “Brine Sink” (not currently present; this hypersaline water body would be a feature of all action alternatives evaluated in the PEIR)

- “Freshwater Marsh” (existing State wildlife areas, federal wildlife refuges, and privately owned duck club marshes located at the Sea as well as anticipated future wildlife refuges supplied by lower Colorado River water)

- “Freshwater Reservoir” (not currently present, but would be included as part of one alternative)

- “Exposed Playa with Water-efficient Vegetation” (does not occur now, but may be formed for air quality management in the future under No Action and other alternatives except Alternative 4 and Alternative 7)

- “Exposed Playa without Air Quality Management” or “Protective Salt Flat” (may be formed in the future under some alternatives)

- “Agricultural Lands” (found throughout the Imperial and Coachella valleys adjacent to the Salton Sea).

ALTERNATIVES EVALUATED

Alternatives evaluated in the PEIR are briefly described as follows and illustrated in Figures 3 through 12:

- Existing Conditions: reflects conditions that have been observed at the Salton Sea in recent years, including results from recent sampling to address identified data gaps;
- No Action Alternative-CEQA Conditions: required by California Environmental Quality Act (CEQA) to reflect existing conditions plus changes that are reasonably expected to occur in the foreseeable future if the project is not implemented;
- No Action Alternative-Variability Conditions: describes a range of estimates of future hydrology considering uncertainty in future conditions to bracket a reasonable range of potential future hydrologic conditions that may influence the development or performance of alternative restoration strategies over the next 75 years;
- Alternative 1 – Saline Habitat Complex I would include Saline Habitat Complex, Brine Sink, and Exposed Playa (AQM);
- Alternative 2 – Saline Habitat Complex II would include Saline Habitat Complex, Brine Sink, and Exposed Playa (AQM);
- Alternative 3 – Concentric Rings would include Brine Sink, Rings (First Ring and Second Ring), and Exposed Playa (AQM):
- Alternative 4 – Concentric Lakes would include Brine Sink, Lakes (First, Second, Third, and Fourth), and Exposed Playa without long-term Air Quality Management (referred to as “Exposed Playa [non-AQM]”) between each pair of Lakes;
- Alternative 5 – North Sea would include Marine Sea, Saline Habitat Complex, Brine Sink, and Exposed Playa (AQM);
- Alternative 6 – North Sea Combined would include Marine Sea, Saline Habitat Complex, Brine Sink, and Exposed Playa (AQM;
- Alternative 7 – Combined North and South Lakes would include Recreational Saltwater and Recreational Estuary lakes (Marine Sea), Saline Habitat Complex, Brine Sink, Freshwater Reservoir, Exposed Playa (non-AQM), and Protective Salt Flat;
- Alternative 8 – South Sea Combined would include Marine Sea, Saline Habitat Complex, Brine Sink, and Exposed Playa (AQM).

Figure 2. Shoreline and Shallow Water Habitat
(photograph courtesy of Doug Barnum, Salton Sea Science Office)

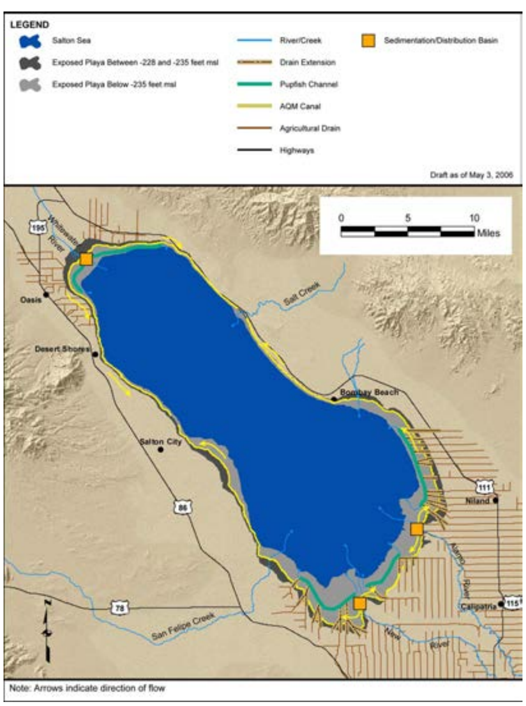


Figure 3. No Action Alternative—CEQA

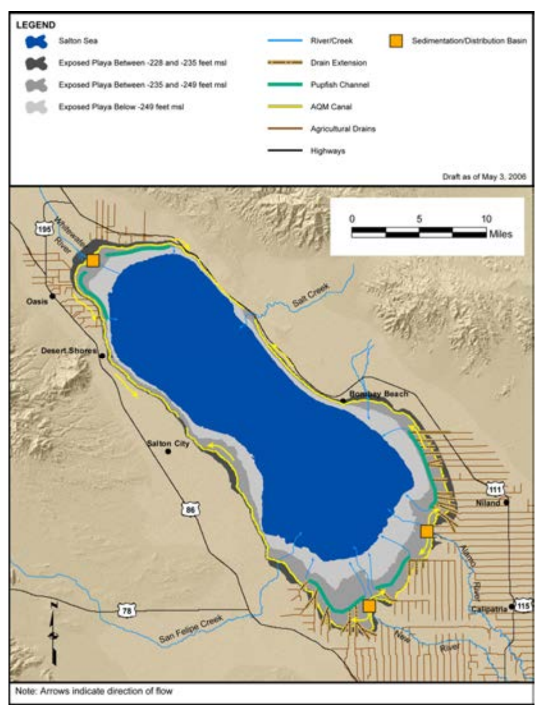


Figure 4. No Action Alternative—Variability

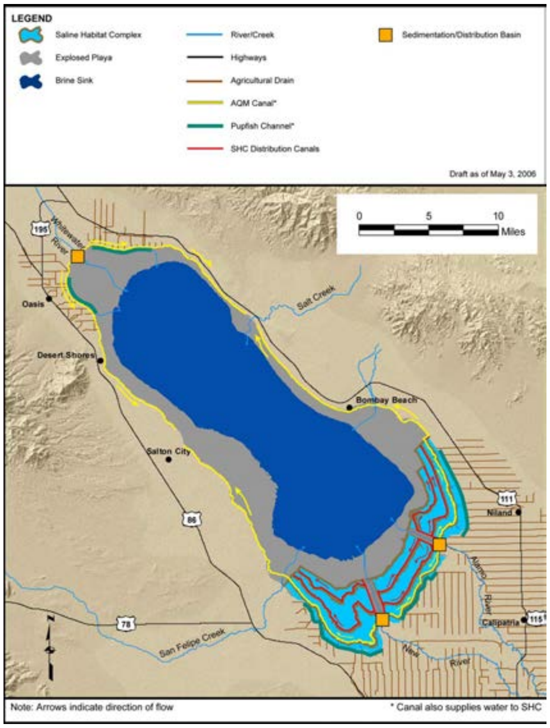


Figure 5. Alternative 1 —
Saline Habitat Complex I

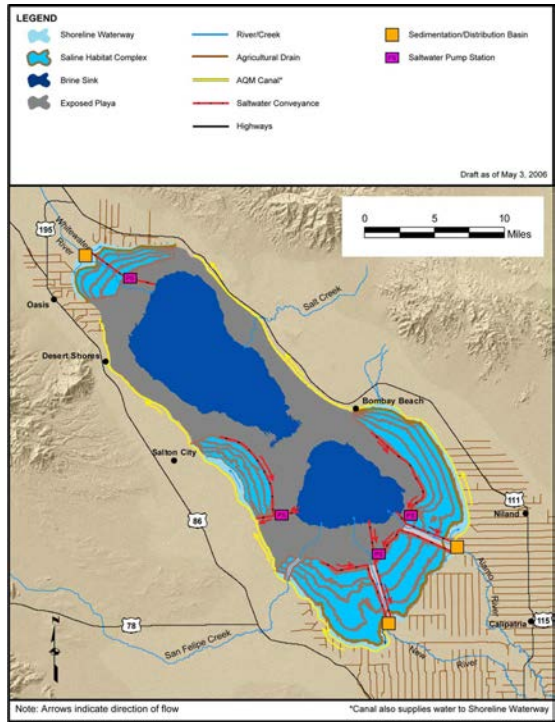


Figure 6. Alternative 2 —
Saline Habitat Complex II

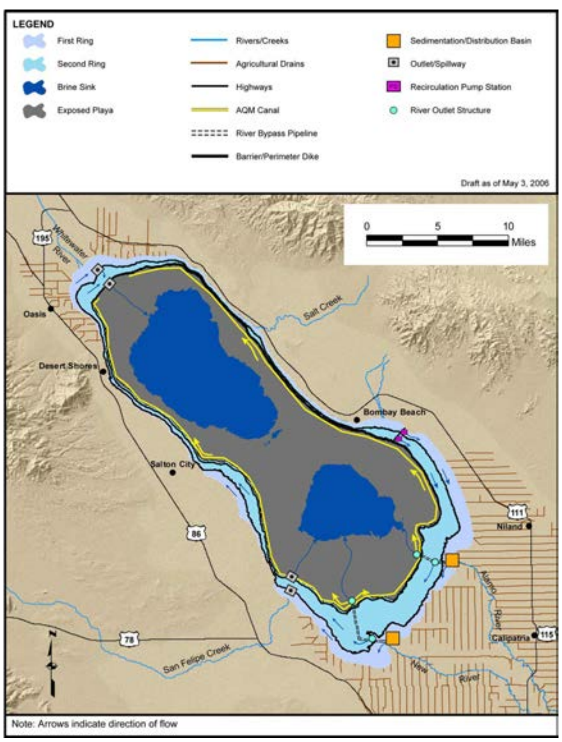


Figure 7. Alternative 3 —
Concentric Rings

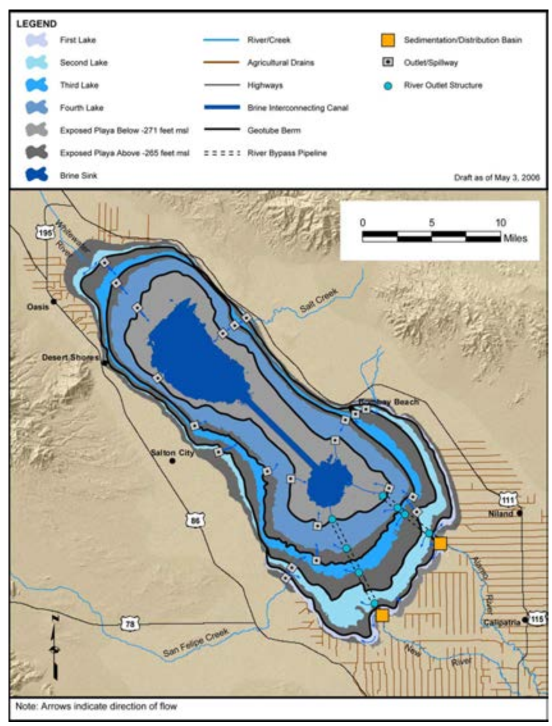


Figure 8. Alternative 4 —
Concentric Lakes

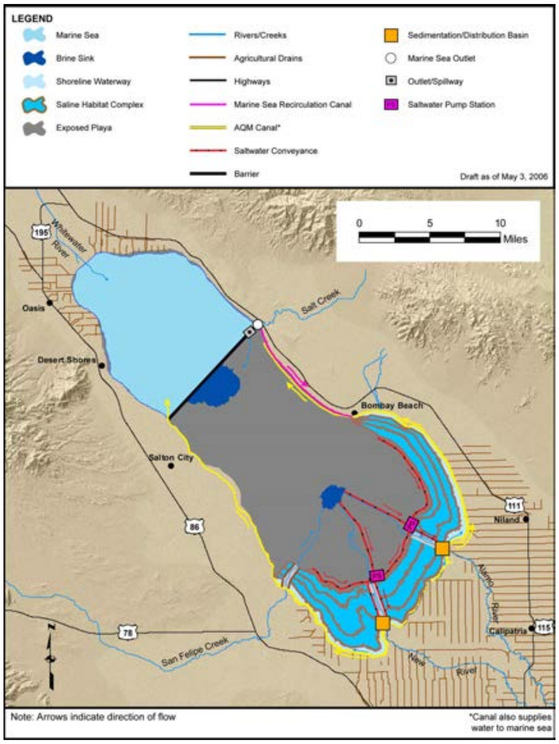


Figure 9. Alternative 5 —
North Sea

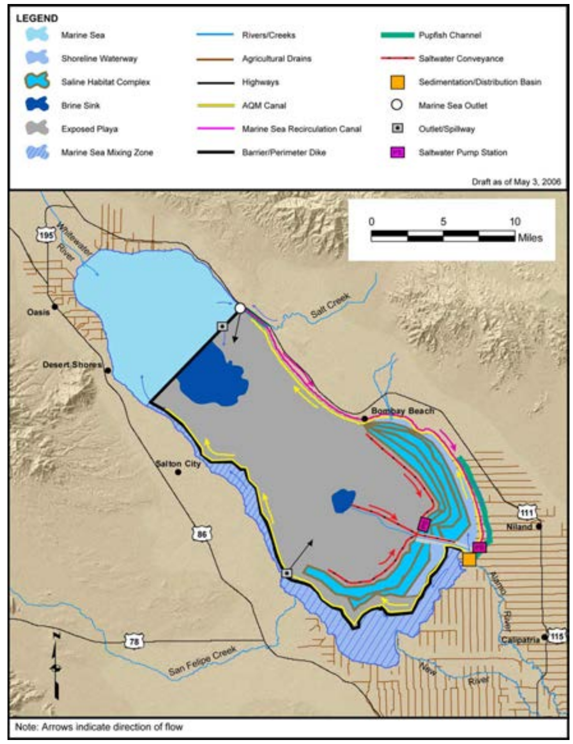


Figure 10. Alternative 6 —
North Sea Combined

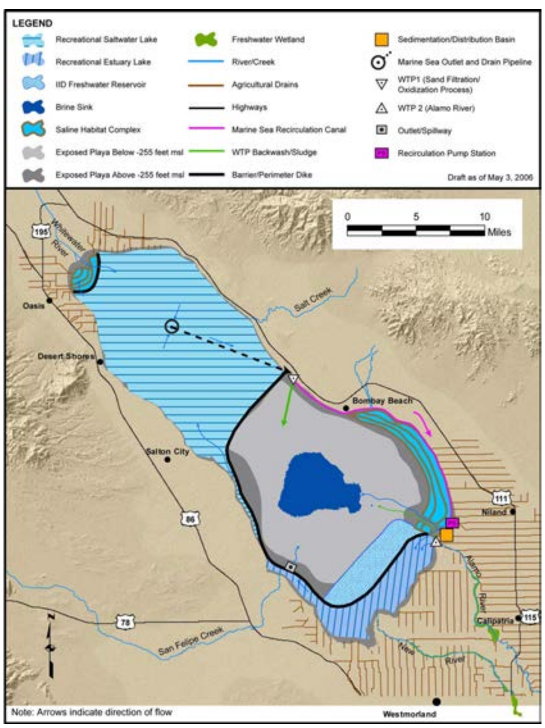


Figure 11. Alternative 7 —
Combined North and South Lakes

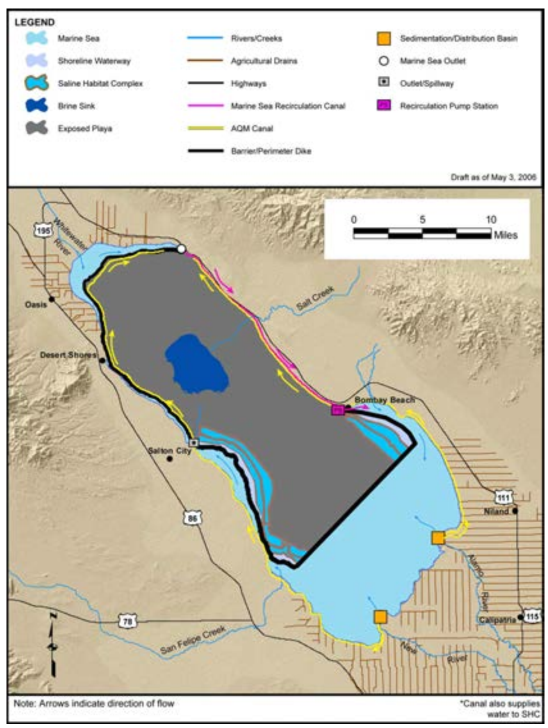


Figure 12. Alternative 8 —
South Sea Combined

CONCEPTUAL SITE MODEL

Ecological exposure to Se under current and future conditions is a function of its concentrations in various abiotic and biotic media and the communities of organisms that may occupy each habitat. Historic and recent environmental sampling shows that Se concentrations in abiotic media (e.g., surface water, sediment, and soils) are related to their location relative to the primary source of Se (i.e., the Lower Colorado River irrigation water) and to the secondary and tertiary Se sources such as agricultural drainage water from influent rivers and the sediments in the Salton Sea where Se is accumulating.

The most important Se food-chain pathway in the Salton Sea begins with accumulation from sediment by benthic invertebrates, particularly pileworms, and includes subsequent uptake by benthic-feeding fish and semi-aquatic birds (Setmire et al. 1993). Selenium is transferred through successive trophic levels in the food chain, sometimes at increasing concentrations. Selenium concentrations in food-chain organisms of tributary rivers and agricultural drains are similar to those of the Salton Sea food chains, but with lower levels at similar trophic levels. Setmire et al. (1993) noted that large birds feeding in rivers do not accumulate nearly as much Se as those feeding in the Salton Sea. In general, Se concentrations at the highest freshwater trophic levels were only one-half of those in the Salton Sea.

Potential exposure pathways for the Salton Sea study area were identified for each habitat type and alternative (for example, see Figure 13). The following potential exposure pathways were evaluated quantitatively for each habitat/alternative:

- Ingestion and/or direct contact with sediment and/or surface water by aquatic and benthic invertebrates;
- Incidental ingestion of, or direct contact with, sediment and/or surface water by fish;
- Food-chain uptake via ingestion of contaminated aquatic plants (including phytoplankton and algae), zooplankton, and/or aquatic/benthic invertebrates by fish;
- Bioaccumulation of Se in fish tissues (whole body and fillet/muscle);
- Incidental ingestion of sediment by semi-aquatic birds;
- Food-chain uptake via ingestion of contaminated sediment, surface water, and dietary components (including phytoplankton and algae, zooplankton and other invertebrates, and/or fish) by semi-aquatic birds;
- Bioaccumulation of Se in semi-aquatic bird eggs; and
- Food-chain uptake via ingestion of contaminated soil, surface water, and prey (terrestrial invertebrates or small mammals) by terrestrial birds.

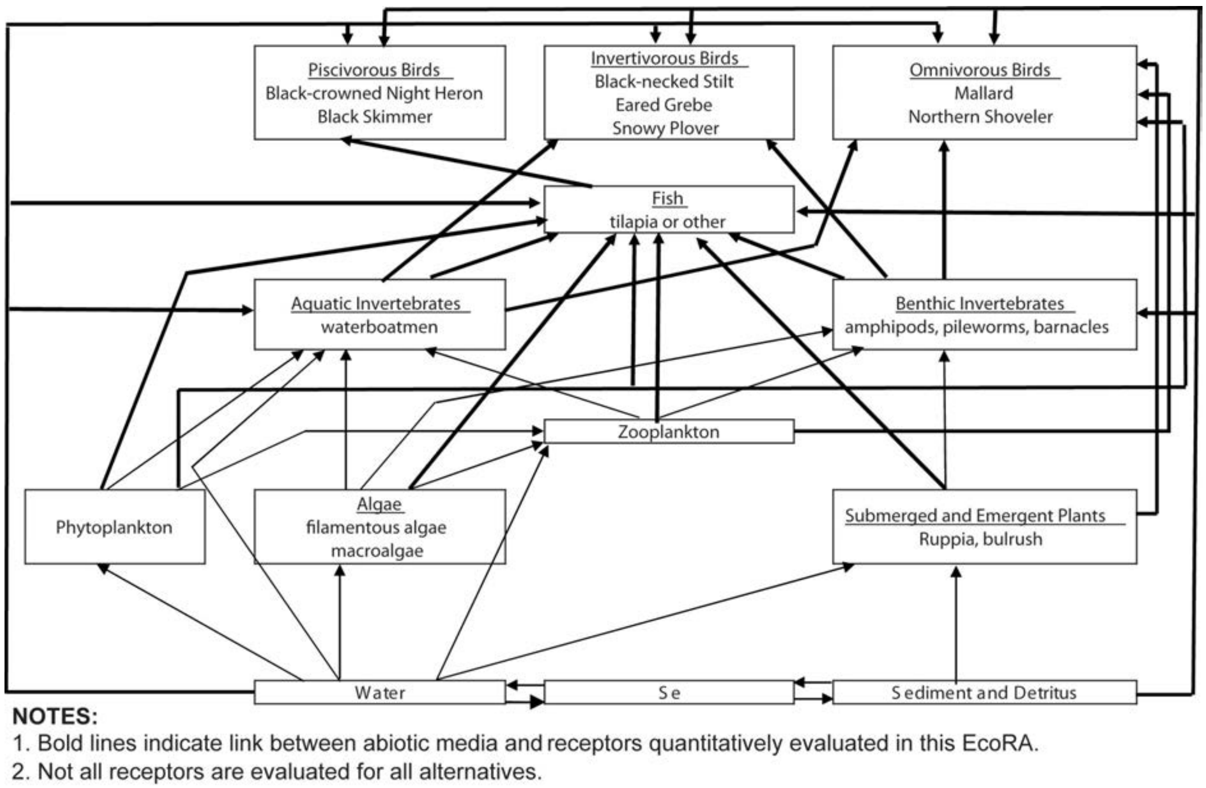


Figure 13. Exposure Pathways and Food Web Relationships in Shoreline and Shallow Water Habitat

REPRESENTATIVE SPECIES/RECEPTORS

The assessment endpoints, measures of exposure, and measures of effect for terrestrial and aquatic/wetland habitats are summarized in Table 1. Consistent with current practice for conducting EcoRAs, representative species or groups of species were selected as receptors for which risk would be evaluated quantitatively for the various endpoints. These receptors were selected on the basis of their likely occurrence in various habitats, their potential exposure to Se (especially through ingestion of food or sediment/soil containing Se), and the availability of toxicity information for them or for similar species.

For Aquatic/Wetland Habitats (marine/estuarine and freshwater), the receptors included aquatic and benthic invertebrates, fish, birds (common species such as black-necked stilt, eared grebe, mallard; and special-status species such as black skimmer and snowy plover) (Table 2). For Terrestrial Habitats, the receptors included western burrowing owl and white-faced ibis (special-status bird species using Agricultural Lands) and loggerhead shrike (in Exposed Playa [AQM], Exposed Playa [non-AQM], and Protective Salt Flat).

Table 1. Assessment Endpoints and Measures

Assessment Endpoint	Measures of Exposure	Measures of Effect
Aquatic/Wetland Habitats		
Aquatic invertebrate community composition, density, and diversity.	Concentrations of selenium in surface water.	Concentrations of selenium in surface water that adversely affect aquatic invertebrate communities.
Benthic invertebrate community composition, density, and diversity.	Concentrations of selenium in sediment.	Concentrations of selenium in sediment that adversely affect benthic invertebrate communities.
Survival, reproduction, growth, and abundance of fish populations.	Concentrations of selenium in sediment, surface water, food items, and tissues of exposed fish.	Concentrations of selenium in sediment, surface water, food items, and tissue that adversely affect fish survival, reproduction, or growth.
Survival, reproduction, growth, and abundance of populations of semi-aquatic bird species.	Concentrations of selenium in sediment, surface water, food items, and eggs of exposed birds.	Concentrations of selenium in sediment, surface water, food items, and tissue that adversely affect bird survival, reproduction, or growth.
Survival, reproduction, growth and abundance of individuals of special-status semi-aquatic bird species.	Concentrations of selenium in sediment, surface water, food items, and eggs of exposed birds.	Concentrations of selenium in sediment, surface water, food items, and tissue that adversely affect bird survival, reproduction, or growth.
Terrestrial Habitats		
Survival, reproduction, growth, and abundance of populations of terrestrial bird species.	Concentrations of selenium in sediment, surface water, food items, and eggs.	Concentrations of selenium in sediment, surface water, food items, and eggs that adversely affect bird survival, reproduction, or growth.
Survival, reproduction, growth and abundance of individuals of special-status terrestrial bird species.	Concentrations of selenium in soil, surface water, and food items.	Concentrations of selenium in sediment, surface water, or food that adversely affect survival, reproduction, or growth of individual birds.

Table 2. Representative Species for Aquatic and Terrestrial Habitats

	Assessment Level and Representative Species																	
	Community Level		Population Level									Individual Level						
			Planktivore	Invertivore		Omnivore				Piscivore	Carnivore	Invertivore			Carnivore	Piscivore		
Alternative/Habitat	Aquatic Invertebrates	Benthic Invertebrates	Fish	Black-necked Stilt	Eared Grebe	American Coot	Mallard	Northern Shoveler	Ruddy Duck	Black-crowned Night-Heron	Loggerhead Shrike	Snowy Plover[a]	White-faced Ibis[a]	Yuma Clapper Rail[a]	Western Burrowing Owl[a]	Black Skimmer[a]	Double-crested Cormorant[a]	Gull-billed Tern[a]
Existing Conditions																		
Salton Sea-Open Water	•	•	•		•			•	•							•	•	
Salton Sea-Shoreline and Shallow Water	•	•	•	•	•		•	•		•		•				•		
Estuary-Alamo River	•	•	•	•	•	•	•			•				•		•		•
Estuary-New River	•	•	•	•	•	•	•			•				•		•		•
Estuary-Whitewater River	•	•	•	•	•	•	•			•				•		•		•
Freshwater Marsh	•	•	•	•		•	•			•				•				•
Agricultural Lands													•		•			
No Action Alternative-CEQA Conditions																		
Salton Sea-Open Water	•	•			•													
Salton Sea-Shoreline and Shallow Water	•	•		•	•		•					•				•[b]		
Estuary-Alamo River	•	•	•	•	•		•									•		
Estuary-New River	•	•	•	•	•		•									•		
Estuary-Whitewater River	•	•	•	•	•		•									•		
Exposed Playa (AQM)											•							
No Action Alternative-Variability Conditions																		
Salton Sea-Open Water	•	•			•													
Salton Sea-Shoreline and Shallow Water	•	•		•	•		•					•				•[b]		
Estuary-Alamo River	•	•	•	•	•		•									•		
Estuary-New River	•	•	•	•	•		•									•		
Estuary-Whitewater River	•	•	•	•	•		•									•		
Exposed Playa (AQM)											•							
Alternative 1: Saline Habitat Complex I																		
Brine Sink	•	•		•								•						
Saline Habitat Complex-South (Drains)	•	•	•	•	•		•					•				•		
Saline Habitat Complex-South (Rivers)	•	•	•	•	•		•					•				•		
Exposed Playa (AQM)											•							
Alternative 2: Saline Habitat Complex II																		
Brine Sink	•	•		•								•						
Saline Habitat Complex-North	•	•	•	•	•		•					•				•		
Saline Habitat Complex-South	•	•	•	•	•		•					•				•		
Saline Habitat Complex-West	•	•	•	•	•		•					•				•		
Exposed Playa (AQM)											•							
Alternative 3: Concentric Rings																		
Brine Sink	•	•		•								•						
First Ring	•	•	•	•	•		•					•				•		
Second Ring	•	•	•	•	•		•					•				•		
Exposed Playa (AQM)											•							

Table 2. Representative Species for Aquatic and Terrestrial Habitats

	Assessment Level and Representative Species																	
	Community Level		Population Level									Individual Level						
			Planktivore	Invertivore		Omnivore				Piscivore	Carnivore	Invertivore			Carnivore	Piscivore		
Alternative/Habitat	Aquatic Invertebrates	Benthic Invertebrates	Fish	Black-necked Stilt	Eared Grebe	American Coot	Mallard	Northern Shoveler	Ruddy Duck	Black-crowned Night-Heron	Loggerhead Shrike	Snowy Plover[a]	White-faced Ibis[a]	Yuma Clapper Rail[a]	Western Burrowing Owl[a]	Black Skimmer[a]	Double-crested Cormorant[a]	Gull-billed Tern[a]
Alternative 4: Concentric Lakes																		
Brine Sink	•	•		•								•						
First Lake	•	•	•	•	•		•					•				•		
Second Lake	•	•	•	•	•		•					•				•		
Third Lake	•	•	•	•	•		•					•				•		
Fourth Lake	•	•	•	•	•		•					•				•		
Exposed Playa 1											•							
Exposed Playa 2											•							
Exposed Playa 3											•							
Exposed Playa 4											•							
Exposed Playa 5											•							
Alternative 5: North Sea																		
Brine Sink	•	•		•								•						
Marine Sea	•	•	•	•	•		•					•				•		
Saline Habitat Complex	•	•	•	•	•		•					•				•		
Exposed Playa (AQM)											•							
Alternative 6: North Sea Combined																		
Brine Sink	•	•		•								•						
Marine Sea	•	•	•	•	•		•					•				•		
Saline Habitat Complex	•	•	•	•	•		•					•				•		
Exposed Playa (AQM)											•							
Alternative 7: Combined North and South Lakes																		
Brine Sink	•	•		•								•						
Marine Sea	•	•	•	•	•		•					•				•		
Saline Habitat Complex-East	•	•	•	•	•		•					•				•		
Saline Habitat Complex-North	•	•	•	•	•		•					•				•		
IID Freshwater Reservoir	•	•	•	•		•	•							•		•		
Exposed Playa 1											•							
Exposed Playa 2											•							
Protective Salt Flat											•							
Alternative 8: South Sea Combined																		
Brine Sink	•	•		•								•						
Marine Sea	•	•	•	•	•		•					•				•		
Saline Habitat Complex	•	•	•	•	•		•					•				•		
Exposed Playa (AQM)											•							

Notes:

[a] Special-status species

[b] Although fish may not be present, concentrations in fish were modeled using site-specific bioaccumulation factors to enable comparisions among alternatives

SALTON SEA RISK ASSESSMENT DATABASE AND EXPOSURE ESTIMATION

Available data from previous studies and from sampling conducted specifically for the project were evaluated for data quality, and data of suitable quality were compiled into an electronic database that included historic and recent Se concentrations in sediment, soil, surface water, and biota. Data on Se in surface sediments from recent studies (1986 to 2005) were used to produce a generalized contouring of Se distribution for the Salton Sea (Figure 14).

Concentrations of Se in potential future sediment, soil, surface water, and biota were modeled as follows:

- Sediment and soil Se concentrations were based on a combination of measured and estimated values (modeled using the Se contour map and interpolating Se concentrations at the intersections [nodes] for a 200-meter grid over the entire Salton Sea footprint).

- Data were assigned habitat codes specific for each alternative and the concentrations were then adjusted by the modeled proportional change in Se loading (calculated based on assumptions for future flows and loading for water from each source entering a specified habitat).

- Measured and estimated sediment Se concentrations for each alternative and habitat were adjusted for future loading.

- Future surface water concentrations were estimated based on the projected flow and loading for each source to derive a single blended concentration for each habitat in each alternative.

- Potential future concentrations of Se in biota were estimated as part of the food-chain modeling for fish and birds.

EXPOSURE CHARACTERIZATION

Three exposure models were used in this EcoRA:

- Concentration-Based Model
  - Aquatic invertebrates exposed to surface water;
  - Benthic invertebrates exposed to sediment;
  - Fish exposed to sediment and surface water; and
  - Birds exposed to sediment (non species-specific [in contrast to the species-specific, dosage-based model described below, this assessment was based on direct evaluation of the sediment concentration]).

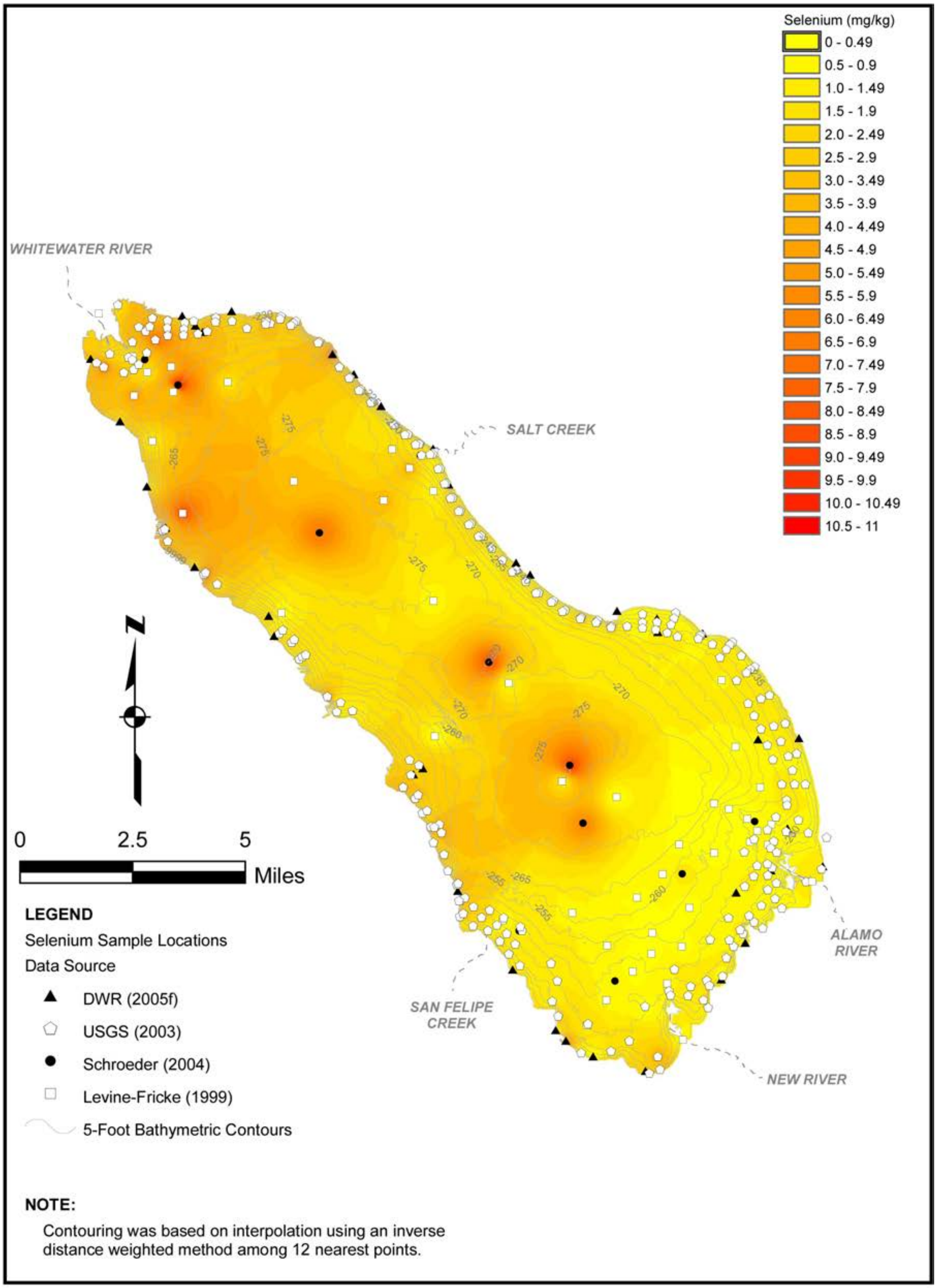


Figure 14. Sediment Selenium Contour—All Samples

- Dosage-Based Model used in estimating the following food-chain exposures:
  - Semi-aquatic birds – uptake of Se from ingestion of sediment, surface water, and food
  - Terrestrial birds – uptake of Se from ingestion of soil, surface water, and food.
- Tissue-Based Model – results expressed as the concentration of Se in selected tissues for which adverse effects have been documented:
  - Fish – measured Se concentrations for Existing Conditions and modeled whole-body concentrations for future using BSAF;
  - Semi-aquatic birds – measured Se concentrations in eggs for the Existing Conditions and modeled egg concentrations for each alternative.

ECOLOGICAL EFFECTS CHARACTERIZATION

Toxicity Reference Values (TRVs) were selected based on the assessment level of the representative species. Where possible, both “low” and “high” TRVs were selected for each receptor (low TRV generally corresponds to little or no adverse ecological effects, such as a no observed adverse effect level [NOAEL]; high TRV corresponds to a greater probability or level of adverse ecological effect, such as a lowest observed adverse effect level [LOAEL]). Results for each receptor were presented for both low and high TRVs, when available, to provide a range of estimated risks.

For representative species that were assessed at the individual level (i.e., most conservative approach, used for special-status bird species), the low TRV was the primary focus. For bird species assessed at the population level (i.e., common bird species), the focus was on the high TRV. For fish, whether assessed at the population level or the individual level, the focus was on chronic water quality criteria and tissue effect levels. For receptors assessed at the community level (aquatic and benthic invertebrates), the high TRV was the primary focus.

RISK CHARACTERIZATION

Risk Estimation focused on quantitative methods to evaluate the potential for risk using the typical hazard quotient (HQ) approach or calculated probability (P) of effect. HQs were developed for two types of comparisons:

- Direct comparisons of exposure point concentrations in sediment, surface water, or tissue to concentration-based TRVs; and
- Comparisons of estimated total exposure dosages via the food-chain uptake model to effects dosage TRVs.

The probability (P) of effects on hatchability of black-necked stilt eggs was calculated based on an available logistic equation (P reflects the chance that $\geq$ 1 egg[s] in a typical clutch of 4 eggs will be inviable).

The Risk Description incorporates results of the risk estimates along with other lines of evidence to evaluate potential Se effects on ecological receptors. The overall potential for risk was scaled (as low, moderate, or high), taking into account the assessment endpoint level for the representative species (community level, population level, or individual level), receptor groups potentially affected, type of TRV (no effects vs. low effects levels), and severity of effects associated with the TRV. Scaling was completed as follows:

- For sediment or surface water Se concentration-based or tissue Se concentration-based exposure models and TRVs (used for aquatic invertebrates, benthic invertebrates, fish, and sediment exposure of birds):

Risk Potential	Hazard Quotient
Low	low TRV HQs < 1
Moderate	low TRV HQ >1 and high TRV HQ < 1
High	high TRV HQ > 1

- For food-chain uptake exposure models and dosage TRVs (used for birds):

Risk Potential	Population-Level	Individual-Level
Low	high TRV HQ < 1	low TRV HQ < 1
Moderate	1 < High TRV HQ < 5	1 < low TRV HQ < 5
High	high TRV HQ > 5	low TRV HQ > 5

Risk contours were developed for the black-necked stilt for each exposure scenario (for examples, see Figures 15 through 18) using sample location-specific sediment concentrations and modeled food-chain uptake. The stilt was selected for the risk contours because it was evaluated in all aquatic habitats and the resulting risk contour would the most complete coverage of the footprint for each alternative. The black-necked stilt was evaluated at the population level, and the hazard quotients depicted on the risk contour are based on the LOAEL toxicity reference value (representing a low probability of effects to the overall population). Total exposure for the black-necked stilt was estimated from ingestion of aquatic invertebrates, benthic invertebrates, sediment, and surface water. The estimated risks were primarily due to ingestion of aquatic invertebrates, followed by ingestion of benthic invertebrates.

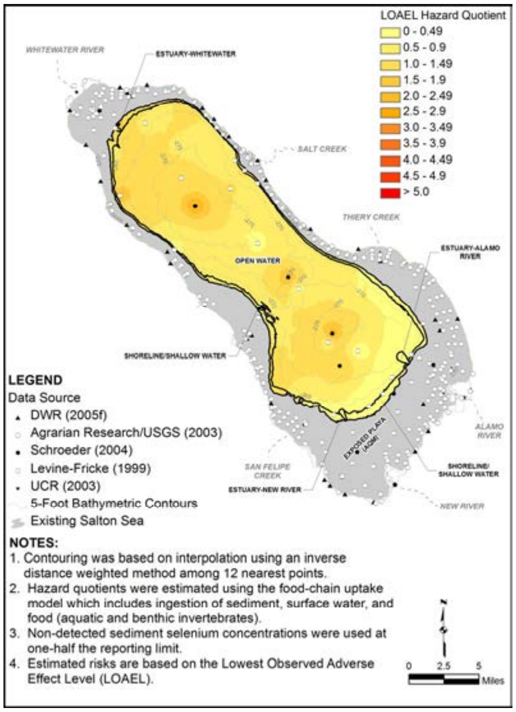


Figure 15.
Estimated Risks for Black-Necked Stilt:
No Action Alternative — Variability Conditions

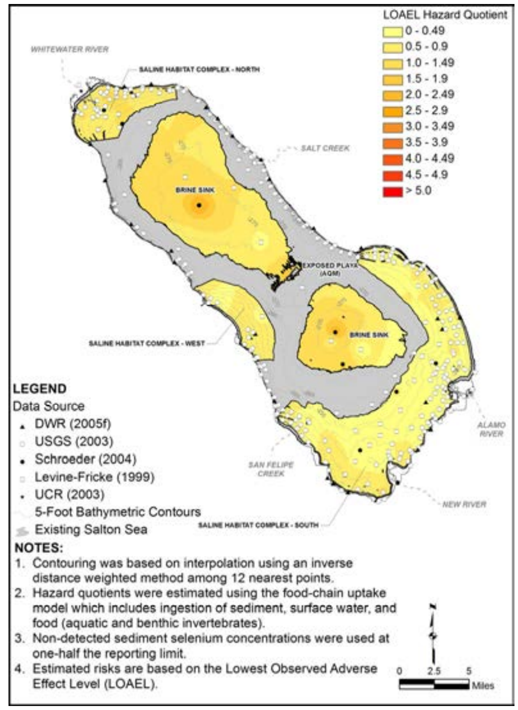


Figure 16.
Estimated Risks for Black-Necked Stilt:
Alternative 2 — Saline Habitat Complex I

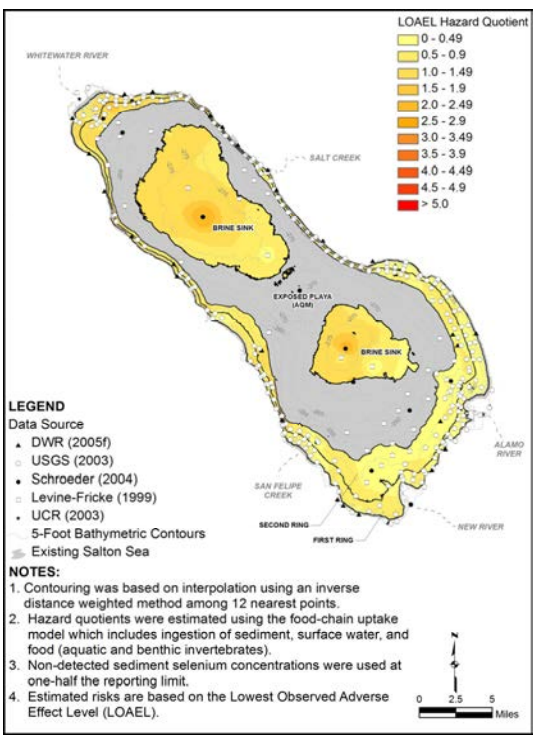


Figure 17.
Estimated Risks for Black-Necked Stilt:
Alternative 3 — Concentric Rings

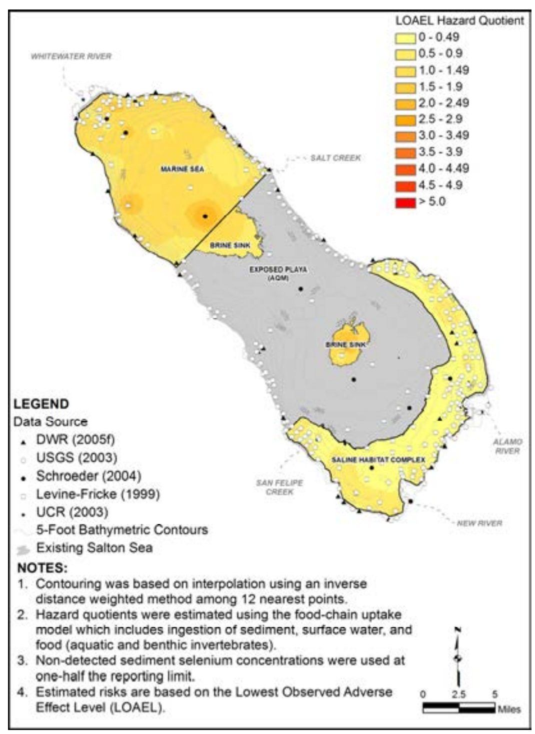


Figure 18.
Estimated Risks for Black-Necked Stilt:
Alternative 5 — North Sea

RESULTS/CONCLUSIONS

Overall results of the EcoRA are summarized in Table 3; alternatives were ranked (on the basis of the percentage of evaluated receptors with moderate or high potential risk) in order of increasing Se risk as follows:

- No Action Alternative-Variability Conditions;
- No Action Alternative-CEQA Conditions;
- Alternative 2: Saline Habitat Complex II;
- Alternative 1: Saline Habitat Complex I;
- Alternative 3: Concentric Rings;
- Alternative 8: South Sea Combined;
- Alternative 6: North Sea Combined;
- Alternative 7: Combined North and South Lakes;
- Alternative 5: North Sea; and
- Alternative 4: Concentric Lakes.

Table 3. Ecological Risk Assessment Conclusions

	Percentage of Evaluated Receptors with Moderate or High Potential Risks[a]			Roll-Up of Risk Potential By Alternative[b,c]			
Alternative/Habitat	Community Level	Population Level	Individual Level	Area Weighted Number of Receptors with Moderate to High Risk	Total Number of Evaluations Conducted	Area weighted percentage of receptors with Moderate to High Risk	Area Weighted Relative Risk Ranking[d]
Existing Conditions	69.2%	41.5%	72.2%	10.1	114	8.83%	na
No Action Alternative-CEQA Conditions	70.0%	27.0%	52.4%	3.3	68	4.83%	NAA-2
No Action Alternative-Variability Conditions	80.0%	32.4%	61.9%	2.6	68	3.88%	NAA-1
Alternative 1: Saline Habitat Complex I	83.3%	54.5%	92.3%	3.9	41	9.45%	2
Alternative 2: Saline Habitat Complex II	87.5%	51.6%	94.7%	5.0	58	8.67%	1
Alternative 3: Concentric Rings	100.0%	63.6%	100.0%	4.5	41	10.87%	3
Alternative 4: Concentric Lakes	100.0%	66.7%	100.0%	13.6	74	18.33%	8
Alternative 5: North Sea	100.0%	72.7%	100.0%	7.4	41	18.02%	7
Alternative 6: North Sea Combined	83.3%	59.1%	92.3%	6.3	41	15.31%	5
Alternative 7: Combined North and South Lakes	80.0%	41.0%	64.0%	12.9	74	17.45%	6
Alternative 8: South Sea Combined	100.0%	68.2%	100.0%	6.0	41	14.58%	4

Notes:

[a] Percentage based on number of representative species evaluated for each habitat (not area weighted).

[b] Roll-up includes only those habitats with supplied water. Exposed Playa and Protective Salt Flat habitats were not included in the roll-up for the alternatives where they occurred (Alternative 4 and Alternative 7). If long term irrigation was included in Alternative 4, the rollup would be different.

[c] Brine Sink habitat is considered to have very little usable habitat. The total acreage of Brine Sink was reduced to 5% usable habitat for purposes of calculating roll-up.

[d] Risk ranking presented in ascending order from best to worst alternative (i.e., #1 is best or least toxic based on selenium risk).

NAA = No Action Alternative

No Action Alternative appears to show the lowest potential Se risk, but the adverse effects resulting from increased salinity were not included in the EcoRA for Se. It is anticipated that no action would result in substantial increases in salinity, which, in turn, would result in significant changes to overall species diversity and abundance of animals associated with the Salton Sea. In addition, potential adverse ecological effects from other general chemistry parameters (e.g., dissolved oxygen, nitrate/nitrite, and ammonia) were not quantified in this EcoRA. These parameters also have the potential to cause adverse effects such as periodic fish kills.

Overall, the evaluation conducted was generalized and may not reflect localized (but sometimes substantial) areas with elevated concentrations of Se.

The highest estimated risks were often associated with the Brine Sink and habitats fed by the Whitewater River (due to elevated Se concentrations in sediment near the river mouth). Any habitats (e.g., Saline Habitat Complex, Marine Sea, etc.) created in the northern-most portion of the existing sea bed (where the highest Se concentrations occur in existing sediment) are expected to result in the highest levels of exposure and risk to fish and birds. As such, the value of habitats created over the northern area sediments would be diminished as a result of Se in the underlying sediment.

Most of the southern portion has generally lower Se concentrations now, but loading in the future will increase Se exposure and deposition to sediment in the southern habitats.

Alternatives that would result in reduced Se loading in habitats most critical to fish and semi-aquatic birds (saline habitat complexes and marine seas), and that would maximize the size of these habitats relative to habitats that typically have greater Se concentrations/potential risk (i.e., brine sinks), would be the best from an ecological risk standpoint.

FURTHER STUDIES

The EcoRA was completed using the best available data and modeling techniques, but there were several limitations/uncertainties that should be reduced when project-specific assessments are performed.

The modeling process used to derive future sediment concentrations was based on the best available information on potential Se mass and loading from various sources to each habitat as defined for the specific alternative. However, the resulting Se concentrations were considered to be fairly conservative estimates, because they do not show large future increases in Se risk in most habitats.

Measured sediment and biota samples were focused on the shoreline and outer margins of the Open Water of the Salton Sea. Very few data were available for the interior portions of the Sea, and very few co-located biota and sediment or water samples were available. Many of the evaluations for various habitats/alternatives were based almost exclusively on estimated concentrations. Further sampling should be conducted to reduce this uncertainty.

REFERENCES

California Resources Agency. 2007. Programmatic Environmental Impact Report. Salton Sea Ecosystem Restoration Program. Prepared by Department of Water Resources and Department of Fish and Game, with assistance from CH2M HILL. State Clearinghouse # 2004021120.

Setmire, J.G., R.A. Schroeder, J.N. Densmore, S.L. Goodbred, D.J. Audet, and W.R. Radke. 1993. Detailed Study of Water Quality, Bottom Sediment, and Biota Associated with Irrigation Drainage in the Salton Sea Area, California, 1988-90. U.S. Geological Survey, Water Resources Investigations Report 93-4014.

LOCAL STAKEHOLDERS PARTICIPATION FOR SMALL SCALE WATER RESOURCES MANAGEMENT IN BANGLADESH

Bashir Uddin Ahmed[1]
Quazi Rezaul Islam[2]

ABSTRACT

As a lower riparian country Bangladesh is largely dependent on 57 transboundary rivers. The upstream courses of these river systems traverse India, China, Nepal, Bhutan and Myanmar. Each day, approximately 3,000 million cubic meters of water discharge into the Bay of Bengal through these rivers. However, flows are much lower during the dry season when surface water is critical to such uses as irrigation, salinity control, habitat preservation, effluent dilution and navigation. Unilateral diversion of water from the transboundary rivers impedes agricultural development using irrigation-fertilizers-modern varieties technology. Thus, sustainable irrigation system is instrumental for the growth of food production. For this, peoples' participation is prerequisite to form social capital in building consensus about the irrigation water uses. Local Government Engineering Department (LGED) has developed a model to facilitate sustainable use of water resources and demonstrated its effectiveness for irrigation management. It develops stakeholders-driven water infrastructure in subprojects each covering 1,000 ha or less. LGED involves local people in subproject planning, design, construction and operation and maintenance (O&M). It has constructed 320 subprojects under the Small Scale Water Resources Development Sector Project. Case study in a subproject in northwestern part of the country found that local stakeholders' participation in managing water resources and operation of water control infrastructure results in excellent performance of irrigation system and improvement of distribution system. This raises irrigation efficiency with productive use of water and releases constraints on land use through facilitating cultivation in three crop seasons and increases the proportion of irrigated area under small farms.

INTRODUCTION

With frequent flooding and drought in Bangladesh, sustainable water resources management is instrumental for rural development. It continues to play a significant role in attaining food security, employment generation, and reducing poverty in the country. The water resources management activities in the country include flood control (FC), drainage (D) and irrigation (I). The FCD developments include embankments, floodwater control and drainage structures and pumps. The irrigation developments with FCD include primary pumping plants, gravity diversion and secondary lift by low-lift pumps and non-mechanized or traditional irrigation by indigenous methods. FCD protects 3.40 million ha and 0.95 million ha is irrigated with FCD (Khan, 1993).

[1] Project Director- Second Small Scale Water Resources Development Sector Project (SSWRDSP-2); Local Government Engineering Department (LGED); LGED Head Quarter, RDEC Bhaban, Sher-e-Bangla Nagar, Dhaka 1207, Bangladesh; pdbashir@yahoo.com

[2] Agronomist-Advisory Technical Assistance; SSWRDSP-2; LGED; LGED Head Quarter, RDEC Bhaban, Sher-e-Bangla Nagar, Dhaka 1207, Bangladesh; qrislam@yahoo.com

The foodgrain production plan of the Government lays major emphasis on development, control and efficient utilization of water resources. This involves both structural and non-structural measures. World Bank (1992) suggests that flood control investments prove to be an appropriate means if Bangladesh wishes to maintain self-sufficiency or surplus of food in the longer run. Of 7.6 million ha of cultivated land under flooded condition, 55.0% is economically feasible for providing improved water control with new flood and drainage managements (BBS, 2004 and Nishat, 1988). Furthermore, WARPO (1991) suggests that irrigable area could possibly be increased through investment in FCD. It was estimated that FCDI could raise the crop area by 1.8 million ha with increase in land use intensity. Since temperatures in the country are suitable for the growth of crops throughout the year, FCDI release the constraints on land use through facilitating cultivation in three seasons on the same land (Islam and Islam, 2001).

The performance of FCDI systems often remained below expectations (Chowdhury, 1988). Many of the earlier FCDI projects were not productive. There has been a serious lack of adequate maintenance and widespread failure of project structures (MPO, 1991). The major cause was identified to address issues related to local participation and distribution of responsibilities between national and local governments in the process of implementation (EIP, 2000). The projects focused mostly on the structural design and inputs from the target beneficiaries were inadequate. Consequently, the project objectives for sustainable water resources management to increase agricultural production were rarely achieved. Accordingly, local stakeholders participation has been recognized as prerequisite for the formation of social capital to build consensus about the use of water resources (Lutz *et al*., 1998). The present study examines LGED experiences on sustainable water resources management involving local stakeholders in Bangladesh.

MATERIALS AND METHODS

The study was carried in 320 subprojects implemented by LGED under SSWRDSP. It was based on information from primary and secondary sources. The primary sources include case study through field visits, household survey and beneficiary interviews. State of participatory water resources management were examined in all the study subprojects at least one year after the construction of physical works. Impacts of participatory water resources management on agriculture and fish production were assessed in 280 subprojects at least two year after the construction. Non-governmental organization (NGO) field workers were involved in the surveys and interviews. Pre-subproject information was collected from secondary sources. These included subproject appraisal and feasibility study and project final report (IWRMU, 2006; SSWRDSP, 2003 and 1994).

RESULT AND DISCUSSION

Participatory Small Scale Water Resources Management

Taking lessons from the performances of the earlier water resources development projects, LGED facilitates sustainable management of water resources with the participation of local stakeholders along with local government institutions involving public and private sectors, communities and individuals in the implementation of SSWRDSP. The Project is consistent with the National Water Policy that has defined the role of the local government institutions and given the mandate of implementing FCDI projects having command areas of 1,000 ha or less.

Participatory Approaches

The primary objective of the participatory water management in the SSWRDSP is to intensify land use and increase in agricultural and fisheries production, employment opportunities and income for rural people. The increase in on-farm activities are to be achieved by removing constraints associated with water resources use. This involves controlled flooding, drainage improvement, floodwater conservation, and irrigation command area development at the union (lowest administrative unit of the local government institution comprising several villages) level. The sustainability is to be ensured by establishing stakeholder-driven water management.

Components

The participatory water management in each subproject consists of three components:

I. Beneficiary participation and WMA development: Mobilizing beneficiaries to participate in the selection, design, implementation and O&M of small scale water resource development system through local government institutions and NGOs.

II. Construction of small scale water resource management systems: Intended for flood control, drainage improvement, water conservation and command area development. This includes agricultural development through appropriate agricultural extension activities, landless access to public water bodies to increase fish production, and environmental monitoring.

III. Institutional strengthening for small scale water resource development: Focused on capacity building of relevant stakeholder organizations, including LGED at the national, zila (district) and upazila (sub-district) levels and key governmental organizations at union and sub-district levels to ensure adequate support for small scale water resource development.

Participatory Process

The overall participatory process in subproject development adopted by the LGED is a combination of two parallel but interrelated processes: one that addresses "Institutional" matters, and the other that addresses "Technical" matters. The institutional matters include subproject identification by the local people and submission through local government institutions, analysis to establish social and environmental acceptability, formation and registration of WMA, and preparation of O&M, agriculture, fisheries and resources mobilization plans. The technical matters include development of information database, subproject processing, analysis to establish technical and economic feasibility, preliminary design, detailed design, contractual process, construction and one year trial operation. The whole cycle of subproject development process is sub-divided into three stages.

Stage 1: Identification and Feasibility. In consultation with local stakeholders, the union parishad (council) initiates subproject proposal. The LGED Sub-district Engineer submits it to the Sub-district Development Coordination Committee for approval. If approved, the proposal is forwarded to the Project Management Office through the LGED Executive Engineer at the district level. The Project Management Office pre-screens the proposal during a multidisciplinary field reconnaissance. This is followed by (i) participatory rural appraisal and (ii) feasibility study. Each subproject is reviewed and approved by District Level Inter-Agency Project Evaluation Committee (DLIAPEC).

Stage 2: Design and Institutional Establishment. Subproject design is prepared and the process of establishing WMA is initiated under the legal framework of the Cooperative Societies Act. Contracted NGO facilitator creates awareness, generates local enthusiasm in the local water resource systems, promote membership enrolment, assist in collection of beneficiary contributions, and conflict resolution. The WMA is registered with the Department of Cooperatives (DOC) and becomes Water Management Cooperative Association (WMCA). The Project Management Office undertakes engineering design work in consultation with stakeholders and discusses for their approval. This process culminates in the signing of a formal implementation agreement by the WMCA, union council and LGED Executive Engineer at district level before tendering for the works or contracting labor societies. To sign the implementation agreement, the WMCA must have achieved enrolment of at least 70.0% of beneficiary households, collection of beneficiary contributions equivalent to an annual O&M requirement and deposited in a joint account by LGED and the WMCA, and approved plans in consultation with people-affected by the environmental mitigation and resettlement.

Stage 3: Construction and First Year O&M. Subproject infrastructure is handed-over to the WMCA one year after completion. The WMCA forms O&M sub-committee and prepares schedule, beneficiary list and maps, and plan comprising operating guidelines, and maintenance and resource mobilization plans. The Project Management Office provides on-the-job training that helps WMCA to (i) undertake annual inspection, (ii) identify maintenance needs, (iii) prepare and implement annual O&M plan, and (iv) collect O&M fees. After this, the WMCA enters into a formal lease agreement with LGED. The WMCA receives support of agricultural extension and fisheries departments to prepare agriculture and fisheries development plans and to organize trainings and demonstrations for WMCA representatives who work as liaison extensionists to the subproject beneficiaries.

Water Resources Development

LGED has implemented 280 subprojects under the first phase of the Project (SSRDSP-1) during 1995 to 2002. It implements 300 more subprojects since July 2002 under the second phase of the Project (SSWRDSP-2) to benefit 180,000 ha throughout the country. Each subproject benefits 1,000 ha or less area where the productivity of land was low due to unmanaged water resources and number of marginal, small and landless farmers was higher. The following discussion on the water management activities is based on the experience in the 280 subprojects implemented under SSWRDSP-1 and 40 subprojects completed under SSWRDSP-2.

In 320 subprojects, 663 hydraulic structures (regulators, sluices, water retention structures, culverts, siphons, and aqueducts), 988 km of embankment and 18 km of irrigation canal have been constructed and 1,406 km of drainage channel has been re-excavated. Based on the use of these infrastructures for water management, the subprojects can be categorized into command area development (CAD), drainage and water retention (DWR), flood control and drainage (FCD) and flood control, drainage and irrigation (FCDI) type (Table 1). The subprojects cover about 239,500 ha and benefit 187,300 ha of cultivated land. Of the total subprojects, about 61.9% control flood and improve drainage covering almost two-thirds of the cultivated land. The remainders benefit 35.5% cultivated land through irrigation development with or without flood control and drainage.

Table 1.Water Resources Development Benefit Area

Subproject		Area		Infrastructures		
Type	No.	Gross (ha)	Benefit (ha)	Structures (no.)	Embankment/ Canal (km)	Re-Excavated Channel (km)
CAD	5	2453	2076	15	18	1
DWR	43	33382	24553	32	4	460
FCD	198	150871	120706	401	904	361
FCDI	74	52784	39933	215	80	584
Total	320	239490	187268	663	1006	1406

Stakeholders Participation

LGED has brought various local stakeholders including all types of farmers together in subproject O&M. The WMCA established at each subproject plays a fundamental role to functionally represent beneficiaries in all processes of the subproject cycle. The stakeholders' participation includes the following institutional and O&M activities in the subprojects areas.

Membership: The WMCAs provide an excellent means to address the needs of a range of special interests. The membership in 320 WMCAs consists of 96,147 males and 32,298 females from an estimated total of 162,958 households. Average membership covers about three-forth of the total households in the subproject areas. The members include marginal, small, medium and large farmers; landless; women and fishers. Women comprised one-third of the management committee of each of the WMCAs and about 25.1% of the total membership.

Capital: These WMCAs have established a capital base in all subprojects through shares and savings by the members. In 320 subprojects, the capital reached Taka 48.9 million (US$0.75 million). The capital is being used to support micro-credit, procurement of agricultural inputs, and other small-scale business enterprises operated by the individual WMCA. The WMCAs have set up micro-credit programs and have loaned to 19,694 male and 8,631 female members. The average size of each loan is about Taka 3,010 (US$46). Since the capital formation the cumulative investments of the WMCAs accrued to Taka 85.3 million (US$1.3 million). The Department of Cooperatives inspects and audits the accounts of the WMCAs. The WMCA members have increased their income with investment of micro-credit on quality seed production, poultry farming, milking cow, beef fattening, vegetable production, aquaculture and seasonal crop storage,

Capability Development**:** The WMCAs members are provided with training to increase their capability in institutional management, capital formation, credit management, agricultural and fisheries production planning, environmental management and subproject O&M. Relevant departments and institutes support the project in training need assessments and organization. LGED has signed memorandum of understanding with the Departments of Cooperatives, Agricultural Extension, Women Affairs, Fisheries and Livestock Service and Ministry of Land to support the subproject beneficiaries. They support WMCAs in institutional strengthening, financial management, use of water bodies, preparation and implementation of agricultural and fisheries production plans and adoption of improved farm practices.

O&M Activities: The WMCAs prepare annual O&M plans and budget and mobilize local resources for the O&M costs. Each WMCA collects annual O&M fund from the farmers at the rate of 3.0% and 1.5% of the total cost for the subproject earthworks and hydraulic structures, respectively. In 2005-2006, the WMCA O&M budget amounted to Taka 17.4 million (US$268,000) and fund utilization was Taka 9.7 million (US$149,000) in 320 subprojects. The O&M fund included voluntary labor contribution.

Impacts

Crop production: Participatory water resources management has generated local enthusiasm for each water resource system. Farmers access to information and their influence on the subproject O&M have increased. This has created opportunity to expand cropped area and increase cropping intensity. Improved water management by the beneficiaries has also resulted in the diversification of crop with the increase in cereal and non-cereal crop area. According to the effect monitoring of 280 subprojects in 2004, the annual cereal production has increased by 242,000 tons and non-cereal production by 157,000 tons. Increase in cereal production is due mainly to cultivation of more rice in the monsoon and maize in the pre-monsoon and wheat in the dry season. On the other hand, more pulse, oilseed, vegetable and spice cultivation in the dry season increases non-cereal production. In Bangladesh, drainage improvement and floodwater control and conservation release the constraints on land use through facilitating cultivation in three crop seasons in the year (Islam and Islam, 2001). This enables small farmers to include cash (non-rice) crops in crop patterns and permits double or even triple cropping on the same land.

Fish production: Subproject design with proper control of the depth and duration of flooding and floodwater conservation ensures growing condition for crops while allowing fish migrate to and from floodplain spawning and feeding areas to effectively minimize impediments to growth of fish population in the subproject areas. This increased annual fisheries production in floodplains by 300 tons and in permanent water bodies by 1,300. Open water fisheries in floodplains and permanent water bodies are the major sources of fish in rural areas. The floodplains include lowland cropped areas where the seasonal flooding depth is more than 90 cm. The permanent water bodies include perennially flooded depressions and river and drainage channel beds.

Labor Employment

Implementation of subprojects increases employment opportunities. The employment related to subproject earthworks is provided to local landless people. Farming in subproject areas is now more labor intensive with year-round demands. Subproject O&M activities also require additional laborers. The Government land (including water bodies), embankments and channels are leased to the WMCA, which promotes income-generating activities for the poor. It was estimated that the annual labor employment increased by 5.3 million person-days in crop production, by 0.26 million person-days in fish production and by 5,700 person-days for subproject O&M.

PROCESS OF WMA: A CASE STUDY

The following case study demonstrates the process of organizing WMA at local level for water resources management. The case study was carried out in Agrani subproject implemented by LGED under the SSWRDSP-1 in the northwest region of the country.

Agrani Subproject

This subproject covers a gross area of 685 ha on the left bank of the Mahananda River between latitude 24°34’and 24°37’ North and longitude 88°17’ and 88°20’ East. It is located in the Zhilim union of Sadar sub-district in Chapai Nawabganj District. Mean annual rainfall in this district is about 1,300 mm. Net cultivated land in the study subproject covers 557 ha. Transplanted aman rice is grown under the rainfed condition in the monsoon season. Flooding often damages the crop. Soils are poorly drained in the rainy season and become very dry during post-monsoon to dry season. These soils are suited for rice cultivation with irrigation. Cultivation of transplanted boro (winter) rice with irrigation in the dry season is the predominant landuse. The crop environment during the dry season is favorable for high solar radiation and evapotranspiration rate, low temperature, and wide variation in day and night temperature. Productivity of the winter rice in this season has grown fastest with the use of modern inputs. Fertilizer responsive modern varieties have adapted to those lands having good irrigation systems. The Mahananda River is the source main source of irrigation water.

The Mahananda River

The Mahananda River originates in the Darjeeling Hills in the extreme northern part of West Bengal state in India (Garrett, 1910 and Islam, 1978). In Bangladesh, the River flows through Chapai Nawabganj district which include the study subproject and meets the Ganges River in neighboring Rajshahi district in the northwest region of Bangladesh (BWDB, 1988 and Rashid, 1991). The barrage across the River in the West Bengal, divert maximum flows through the main canals for fulfilling irrigation and hydropower requirements (Majumder, 2005). It also regulates flood flows. The conveyance and distribution systems are designed on the basis of peak irrigation requirements in the post-monsoon period. The use of the Mahananda River flow is even limited to fulfilling the agreed share of the neighboring Bihar state in India. As a lower riparian country, Bangladesh is largely dependent on transboundary rivers for the management of its water resources. In recent years, increase rice production on the Mahananda River basin indicates that irrigation demands could exceed the water availability in the river. Moreover, water shortages are often compounded by inefficient uses.

Pre-Subproject Situation

The irrigated area covered 44.2% of the net cultivated or potential irrigable area. The subproject area is elevated and pumping up water for irrigation from the Mahananda River on the northwest involves a high lift. In the past, flow in the Mahananda River was adequate to meet the irrigation requirements. However, unilateral withdrawal of water by India upstream reduced the flow in the dry season since the 1980s. During the period of April-May when irrigation requirement reached peak, 80.0% dependable water level was found to be 12.5 m in some years. The level was not sufficient to allow pumping from the shore with full capacity. The concern grew stronger as frequent drought in the post-monsoon season required supplementary irrigation. This led to efficient use of water on irrigated land. The techniques available for irrigation included practices such as lifting water from the Mahananda River to provide on adjacent lands directly by 300 m brick-lined canal and to conserve in a manmade reservoir for second lifting using low-lift pumps to irrigate crop on distant highlands through 1,500 m earthen canal. The double-lifting irrigated lands covered 65.0% of the total irrigation area. Irrigation was uneconomical in the double lifting lands for high operation cost, inadequate section of the earthen canal and excess water loss. However, farmers had no choice because rice production in the monsoon season was uncertain both for flooding and drought. There was little incentive for these farmers for high irrigation costs and low production. Moreover, farmers were more concerned with poor credit availability, which made difficult to procure quality seeds, fertilizers and other inputs. Since water was irrigated through earthen canals, farmers were worried about water shortage during the peak season, decrease in water level in the reservoir and low flow in the Mahananda River. The local people had no idea how to solve the problem.

Organization to deal with the problem was initiated by local people interested for water management. A committee was formed with representatives from the farmers on highlands and lowlands from adjoining and distant areas. The committee in consultation with the union council, agricultural extension agent and community leaders familiar with local water resources approached government departments for intervention. Simultaneously, the committee attempted to improve water management. They focused on the inadequate water availability, water losses, low coverage and high irrigation costs. The strategy of the committee was to reduce irrigation cost with more area under irrigation using the available water resources. The committee actively tried to achieve these goals. Expansion of existing command area through level fields, earthen canals, rotational irrigation and other appropriate methods was attempted. The committee rented a floating pump with 12.5 cusec capacity. With this total irrigation capacity of the pumps reached to 27.5 cusec. The floating pump helped to lift water with full capacity throughout the year. However, damage of the brick-lined canal, second lifting and distribution of water by earthen canal would still cost irrigation high. Moreover, water demand in the dry season by the winter rice growers was difficult to meet for the inadequate conveyance capacity of the damaged canals.

Subproject Construction

In 1996, the committee approached LGED district office at Chapai Nawabganj through their union council to improve irrigation facilities and increase area under irrigation. The subproject was reviewed and approved by the sub-district and district level committees. The subproject beneficiaries deposited 10.0% of the construction cost to the LGED district office as required for subproject construction. The SSWRDSP-1 design called for beneficiaries to contribute to capital costs at a rate that was approximately equivalent to one years O&M. The beneficiary contribution was collected prior to signing the implementation agreement. According to total households along with the amount of land they own within the subproject area were identified and listed. The beneficiary contribution was then collected on the basis of the land owned by the individual beneficiaries and deposited to a bank account opened by LGED. It was later credited to the subproject for construction of the physical works. A feasibility study was carried out by the LGED. Design of irrigation water distribution was initiated after the subproject was found to be feasible. The subproject construction started in 1996. The physical works included 4,055 m main lined canal, 750 m branch lined canals, two siphons, three aqueducts, one sluice and four culverts. The construction required Taka 22.6 million (US$0.42 million).

Beneficiaries Organization: The LGED Socio-economist at district and Community Organizer at sub-district offices brought local stakeholders together with the formation of a WMA in the subproject area. An NGO Facilitator was employed in subproject area to organize the local stakeholders and strengthen the WMA. It was registered to Department of Cooperative in 1997 and called as Agrani subproject WMCA. The WMCA members included the people who benefited directly or indirectly by the irrigation in the subproject area. The WMCA has now 855 members including 186 women from 62.0% of 1,379 households in the subproject area. It has developed own capital with shares and savings by the members. The capital now reached Taka 233,290 (US$3,500). The WMCA has introduced micro-credit program. It disbursed Taka 1.1 million (US$16,000) among 415 male and 64 female loan recipients in 2006.

Subproject Benefit

The subproject construction works completed in 1998 and operation started in the dry season of the following year. The irrigation area increased from 246 ha to 537 ha occupying 96.4% of the net cultivated area in 2005. This required increase in pump capacity to 43 cusec (1.14 cumec). Single lifting area now covers 78.8% of the irrigation area and double lifting is practiced in 21.2%. Irrigation expenditures reduced particularly for the increase in irrigation area and decrease in diesel procurement and canal repairing costs (Fig. 1). Occasional rainfalls in the late dry or early pre-monsoon season further reduce the expenditures as in 2001. The water users now pay 16.0% less for irrigation to their lands compared with that required during the pre-subproject period. The WMCA plans to expand irrigation area with the increase in canal lengths using the excess fees. Accordingly, irrigation fees are collected at higher rate than the actual expenditures.

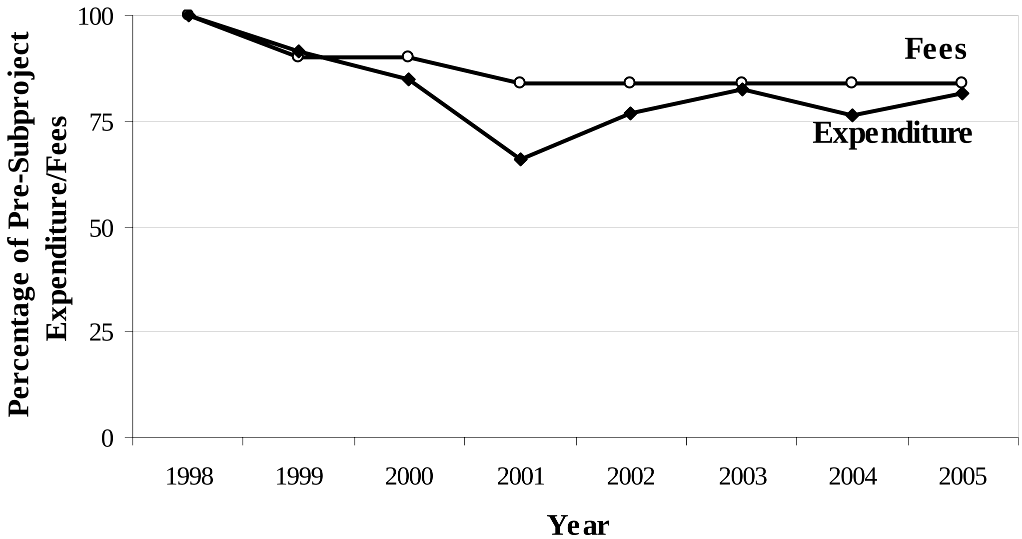


Figure 1. Changes in per ha irrigation expenditures and fees (dry season)

Single lifting now helps more farmers obtain higher income from irrigated crops. Moreover, low irrigation cost enables farmers to use inputs at recommended rate and increase output per unit area. In a field study in 1999, it was observed that per ha Taka 29,280 (US$540) was required in double lifting irrigation area to produce modern variety of rice crop in the winter season (Fig. 2). The production cost for the same crop was Taka 26,680 (US$490) per ha in single lifting irrigation area. The irrigation charge accounted for 30.4% of the crop production cost in the double lifting area and 14.0% in the single lifting area.

LGED entered into a formal lease agreement with WMCA to take full responsibility for the O&M of the irrigation system. The purpose was to ensure that sufficient ownership of subproject infrastructure had been established and to create a basis on which the O&M responsibilities would become that of the local stakeholders. The lease agreement was signed in 1999, one year after physical construction had been completed to allow for a trial O&M period during which defects were identified and rectified. LGED managed staff, local stakeholders and union council members received training under the capacity building program to establish and nurture WMCAs that have the capability and the interest to undertake long-term and sustainable O&M of the irrigation infrastructures. The WMCA management committee prepares annual O&M plan and budget and mobilizes local resources for the O&M costs. The agricultural sub-committee prepares and implements annual crop production and water distribution plans. The O&M sub-committee is responsible for the implementation of annual plan and collection and utilization of O&M funds. Annual O&M fund collection was Taka 400,000 (US$6,100) in 2005. LGED delivers comprehensive training programs with improved training materials to WMCA management committee, agricultural and O&M sub-committees and general members including beneficiary farmers.

Per hectare production cost for irrigated winter rice (modern variety) production

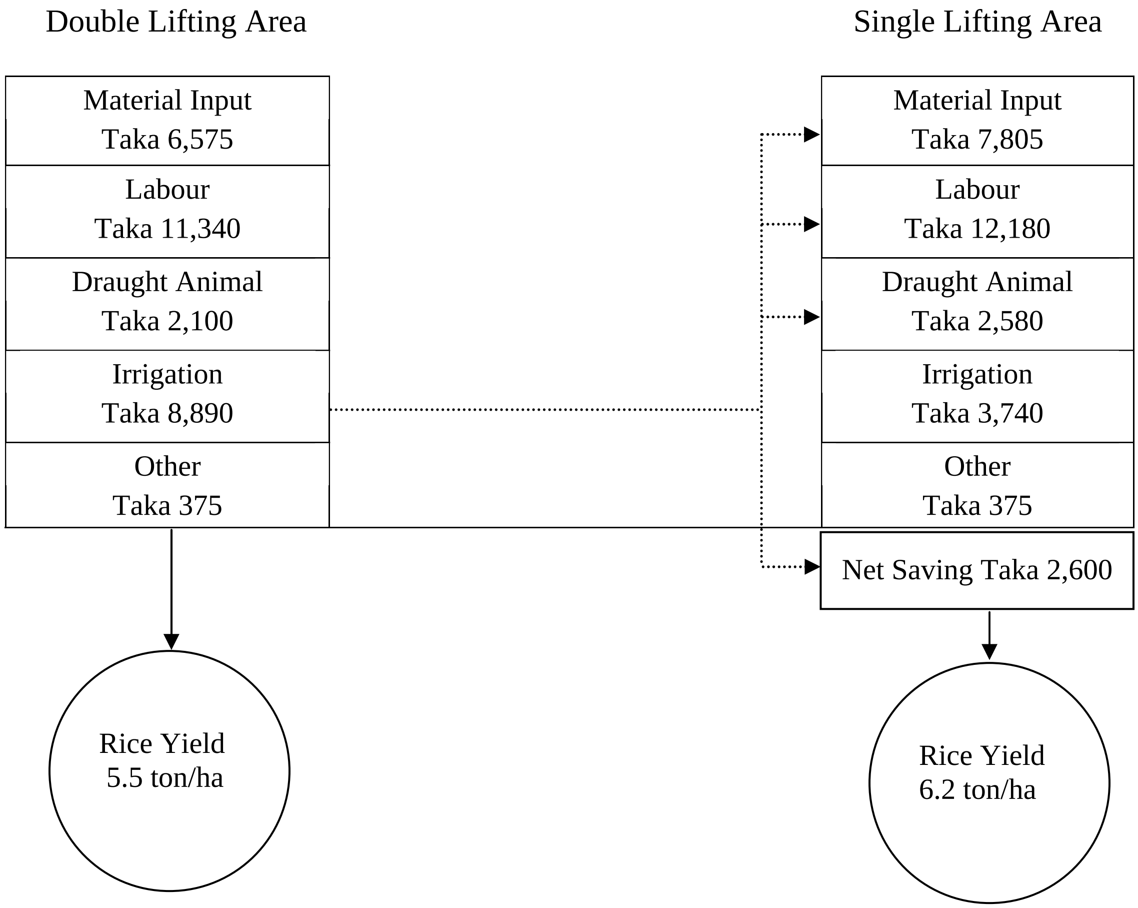


Figure 2. Impact of reduced irrigation cost on the input uses and yield level (broken line shows use of the surplus money available for the reduction of irrigation cost)
1Taka=US$0.016

Field study in 2005 showed that about 66.4% of the rice growing area was provided with supplementary irrigation in the monsoon season and 35.2% in the pre-monsoon season. Annual cropped area has increased by 278 ha and crop intensity by 50.0%. LGED supports subproject beneficiaries to adopt improved farm practices through on-farm training and demonstrations by the Department of Agricultural Extension. Field level extension workers of the Department of Agricultural Extension support WMCA in preparing and implementing annual crop production plan and monitoring of irrigation water uses. The irrigation development with the application of improved farm practices and use of high-yielding modern varieties contributes to increase rice production. Area under modern rice varieties increases in the monsoon season for the supplementary irrigation and in the winter season for the improvement of conveyance capacity of the canals. The irrigation also contributed to increase average rice yield levels by 2.1 ton/ha. Crop production is now more diversified with 41.0% of the total crop area under non-cereal compared to 18.0% during the pre-subproject period. Annual cereal production increased from 2,065 tons to 3,215 tons. The non-cereal production increased to 3,220 tons from 375 tons. The number of farm households now use irrigation water is 2,260 compared to 1,389 during the pre-subproject period. The increased crop production provides additional employment opportunity. Irrigation development has doubled the farm labour wage rate. The subproject is now well-known as '*Bwishwa Khal*' (universal canal).

CONCLUSIONS

Involving local stakeholders thorough WMAs in water management is advantageous for three reasons. First, WMAs as local organizations are effective in generating and securing compliance with rules for the use of water which is a common property. Second, WMAs involve local stakeholders in the development of effective water management practices. Third, devolution of responsibilities to the WMAs externalizes O&M expenditures to local communities from the government fund and reduces overall crop production costs by creating conditions in which cooperative, agricultural and other supporting agencies become more efficient and effective through collaboration with beneficiaries.

The WMAs regulate water uses, provide a forum for resolving conflicts among local stakeholders and provide a channel for the representation of on-site and off-site stakeholders groups in the negotiation of water resource use. WMAs mobilize and deploy significant resources, both in cash and kinds that are needed to implement sustainable water resources management. The special nature of WMAs are that they provide a basis for collective actions, which include building consensus about water use problems and needed solutions, seeking and disseminating information about these, coordinating actions, designating rights and responsibilities as well as ensuring accountability. According to Cernea (1993) and Uphoff (1992), self-organizing groups for common property uses management are only one subset of the local organizations that use water resources and form the tapestry of local institutional arrangement. In the subprojects of SSWRDSP, the WMCAs define rules in water resources management and O&M of infrastructures for individuals or groups. Such as monitoring state of water control structures, irrigation and drainage canals, water level, water use benefits and O&M fund collection. Such roles involve applying sanctions for noncompliance with the locally defined rules for water management.

Cernea (1987) found in a study of 25 agricultural projects several years after completion that those which had made an effort to build local organizations such as water user associations, had been able to sustain high rates of return. On the other hand, projects without local organizations had 5-10 times lower rate of return than anticipated. The WMAs that build their experience in working together in the subprojects of SSWRDSP is an important ingredient in the capacity of local stakeholders to manage their affairs successfully without dependence on outside agencies.

REFERENCES

BBS. 2004. Yearbook of Agricultural Statistics of Bangladesh 2001. Bangladesh Bureau of Statistics. Dhaka.

BWDB. 1988, Morphological Features of the Major Rivers of Bangladesh-Part 1, Bangladesh Water Development Board.

Cernea, Michael M. 1993. Culture and Organization: The Social Sustainability of Induced Development. Sustainable Development 1 (2):18-29.

Cernea, Michael M. 1987. Farmers Organizations and Institution Building for Sustainable Development. Regional Development Dialogue 8(2): 1-24.

Chowdhury, Y. A. 1988. Institutional Analysis: BWDB and BADC. Vol. V: Institution. UNDP/ASR. Bangladesh.

EIP. 2000. Learning Lessons: 20 Years of EIP Experience. Early Implementation Project. Environmental Geographic Information System. Bangladesh.

Garrett, J.H.E. 1910. Bengal District Gazetteers: Nadia, Calcutta.

Islam, MA. 1978. The Ganges-Brahmaputra River Delta", Journal of University of Sheffield Geological Society (l).

Islam, M. N. and Q R Islam. 2001. Small Scale Water Resources Development for Flood Damage Control and Floodwater Conservation in Bangladesh. ICID. 1st Asian Regional Conference. Seoul.

IWRMU. 2006. Annual Effect Monitoring and Evaluation Report 2004-2005. Integrated Water Resources Management Unit. LGED. Bangladesh.

Khan H R.1993.Water development activities and their impacts on wetlands. In Nishat, et al (eds.) Freshwater Wetlands in Bangladesh: Issues and Approaches for Management. IUCN:23-32.

Lutz, E. H. Binswangar, P. Hazel and A. McCalla, editors. 1998. Agriculture and the Environment. World Bank. Washington, DC.

Majumdar, B.S. 2005. The information technology-based improved management system for the Teesta Barrage Project. Modernization of irrigation system operations: proceedings of the fifth ITIS. FAO.

MPO, 1991. Evaluation of Historical Water Resources Development and Implications for National Water Plan. Master Plan Organization (now Water Resources Planning Organization). Bangladesh.

Nishat, A. 1988. Large Scale Water Development. UNDP/Bangladesh Agriculture Sector Review.

Rashid, H E. 1991. Geography of Bangladesh, University Press Ltd., Dhaka.

SSWRDSP 2003. Project Final Report. January 2003. Small Scale Water Resources Development Sector Project. LGED. Bangladesh

SSWRDSP. 1994. Feasibility Study. Agrani Irrigation Sub-project (CSP-4). LGED. Bangladesh

Uphoff, Norman Thomas. 1992. Learning from Gal Oya: Possibilities for Participatory Development and Post-Newtonian Social Science. Ithaca, N.Y.: Cornell University Press.

WARPO. 1991. Evaluation of Historical Water Resources Development and Implications for National Water Plan. Water Resources Planning Organization. Bangladesh.

World Bank. 1992. Bangladesh Food Policy Review: Adjusting to the Green Revolution. Volume I: Main Report.

WATER USER PARTICIPATION IN EGYPT: AN INCREMENTAL PROCESS TOWARDS IRRIGATION MANAGEMENT TRANSFER

Eng. Moamen El-Sharkawy[1]
Eng. Amira El-Diasty[2]
Dr. Khaled Wassief[3]
Eric Viala[4]

ABSTRACT

Experiences establishing Water User Associations (WUAs) in Egypt have been carried out for the past 15 years, with increasingly promising results. Most of these activities have been pilot projects aiming to demonstrate the benefits and sustainability of WUAs. They were consequently implemented through a centralized and resource-intensive process and focused on limited numbers of associations.

Since 2003, the Ministry of Water Resources and Irrigation (MWRI) has adopted as policy the large-scale development of Branch Canal WUAs. With support from USAID, about 600 branch canal WUAs (BCWUAs) have since been established, covering 15% of Egypt's irrigated area and involving half a million farmers and residents.

In order to achieve this impressive outcome, a different approach has been developed and implemented, emphasizing the direct involvement of MWRI field staff and a partnership between water users and MWRI managers. This paper also argues that the conventional approach of forming WUAs by focusing on water users, and empowering them to take over the O&M responsibilities of irrigation systems, is not adapted to the Egyptian context.

INTRODUCTION

Experiences establishing WUAs in Egypt have been carried out for the past 15 years, with increasingly promising results. The first attempts were led by the MWRI in the late 80s early 90s under the USAID funded Egypt Water Use and Management (EWUP) and the Irrigation Management Systems (IMS) projects. The USAID and World Bank-funded Irrigation

[1]Senior Assistant Director of Works, Integrated Water Management Unit, Ministry of Water Resources and Irrigation, Cairo, Egypt
[2]Senior Director of Works, Integrated Water Management Unit, Ministry of Water Resources and Irrigation, Cairo, Egypt
[3]Director of Water Communication Unit, Ministry of Water Resources and Irrigation, Cairo, Egypt
[4]Senior IWRM Resident Advisor, USAID-funded LIFE-IWRM Project managed by International Resources Group, Cairo, Egypt - eviala@iwrmeg.org - peviala@aol.com

Improvement Projects (IIP) went along by establishing mesqa[5] WUAs, while the Fayum Water Management Project (FWMP) formed branch canal-level Water Boards. Recently the Water Boards Project has initiated the establishment of District[6] Water Boards.

Apart from the IIP projects, where WUA establishment mostly supports mesqa structural improvement, the other projects aimed to prove the feasibility and sustainability of WUAs. They consequently focused on limited numbers of associations, and used a resource-intensive formation process, with implementation and monitoring done at central level. They were able to sensitize water users and MWRI staff to the benefits of water user participation.

Starting in 2003, the MWRI has initiated the large-scale formation of BCWUAs, starting first with 94 of them in 4 pilot irrigation districts, and now with several hundreds of them over five entire irrigation directorates. In order to reach this ambitious goal, it has quickly become clear that the former establishment process, however successful, was too time and resource-intensive to allow easy replication. To address this concern, a revised BCWUA formation process has been developed and implemented, as presented hereafter.

KEY PRINCIPLES FOR LARGE-SCALE DEVELOPMENT OF BCWUAS

BCWUA formation pilot approaches implemented in Egypt so far, even if successful, have the following deficiencies when considering large-scale replication:

- They select geographically and socially promising areas to establish BCWUAs; large-scale replication implies that entire irrigation districts and directorates are to be covered, without restriction;
- They institutionalize centralized WUA formation teams which end up constituting a third party between water users and MWRI field staff, thus complicating communications and preventing a direct partnership;
- They devote time and resources to the formation process itself, less on the definition of BCWUA functions and the strengthening of BCWUA activities;
- They tend to guide MWRI staff and water users step by step along the process, with extensive technical assistance, training and awareness; this approach, while essential to demonstrate results at a pilot stage, cannot be replicated all over Egypt; and
- Heavy project support makes for unsustainable and non-replicable results, with limited capacity-building of MWRI staff at local level, and limited awareness raising among uninvolved water users about the opportunity that WUAs represent.

These pilot approaches, while essential to demonstrate initial results, cannot thus be applied over large areas of Egypt. Large-scale replication implies rationalizing the BCWUA formation process, achieving concrete results and getting tangible benefits for water users, and also accepting that not all associations will succeed (some may be inactive or inefficient because of

[5] Mesqas are tertiary level canals, privately owned and serving 50-300 feddans/acres through marwas (plot ditches). They are supplied by state-owned branch canals (secondary canals serving 500-5000+ fedddans/acres).
[6] The MWRI is organized into regional delegations (general directorates) and local delegations (districts).

pre-existing community conflicts, lack of willingness, focus on other -not water related- issues, etc.).
Over the past two years, the MWRI Integrated Water Management Unit (IWMU) has led large-scale formation of BCWUAs with support from the USAID-funded LIFE-IWRM[7] Project.

A preliminary step was to simplify the structure of the MWRI by establishing Integrated Water Management Districts[8] (IWMDs) as sole local delegations (thus merging pre-existing irrigation and drainage districts). The revised approach is then based on the following principles:

- Increasing awareness that BCWUAs are an opportunity with clear benefits for motivated and determined MWRI staff and water users;
- Building the capacity of MWRI staff, chiefly at district level, to support BCWUA development, now and in the future;
- Providing a streamlined clear process for forming BCWUA;
- Empowering IWMDs to directly form BCWUAs, since this:
  - Promotes a <u>direct partnership between BCWUAs and IWMDs</u> (with IWMDs as a "single window" contact for water users to provide and receive information, express needs and priorities);
  - Reinforces the <u>IWMD as sole MWRI agency</u> at district level; IWMDs represent a unique venue to coordinate all water management activities and implement water projects, thus resulting in more appropriate and timely decision-making, more sustainable implementation and significant economies of scale;
  - Ensures <u>sustainability</u> (after project ends) by building the capacity of IWMD staff;
  - <u>Reduces the cost</u> of forming BCWUAs over all of Egypt by using existing local staff instead of using a specific implementing entity.
- Identifying clear benefits for both water users and IWMD staff; and
- Emphasizing the fact that BCWUAs are complementing the role of IWMD staff, not replacing it.

The main strength of the revised approach is to focus on actual activities and outputs to ensure that water issues are tackled and tangible benefits achieved, in terms of improved allocation of water resources and O&M funds, better resolution of water disputes, etc. This is eventually what builds the credibility and sustainability of BCWUAs (as opposed to optimal administrative and organizational procedures, which can be improved over time).

The activities needed to implement this approach and support BCWUA formation by IWMDs include the following:

- Standardization of the formation process (guidelines and training modules);
- Training (formal/classroom and On-The-Job coaching) of IWMD staff;
- Monitoring of IWMD and BCWUA performance; and

---

[7] Livelihoods and Incomes From the Environment Program, Integrated Water Resources Management Project.
[8] See references.

- Awareness raising regarding BCWUA benefits.

PROCESS OVERVIEW

The BCWUA formation process involves five main steps:

- Introduction/Orientation: MWRI officers (especially IWMD managers) get acquainted with the BCWUA formation process, and a Water Advisory (WA) Team is selected and assigned in each IWMD;
- Preparation: geographical and social data is collected to identify where BCWUAs will be formed and to identify key water users; BCWUAs are delineated through canal grouping;
- Establishment: Key water users are informed about BCWUAs, sensitized to the benefits and convened to elect Board members and a chairperson; these representatives are acknowledged through a MWRI decree and invited to sign a Memorandum of Understanding (MOU) with the MWRI;
- Activation: BCWUA Boards prepare their own Internal Regulations, and collaborate with IWMD staff to identify key water issues, assess solutions and define actions and activities to be implemented; and
- Participatory Water Management: BCWUAs get involved in activities under four themes: water distribution, maintenance of waterways and structures, water quality, and communications and administration.

Step	Objective	Support activities	Duration	Output
Introduction	To raise awareness of local MWRI staff regarding water user participation	Introduction /Orientation Training	1 month	Mobilized IWMD staff, formed IWMD-WA Team
Preparation	To gather information on branch canals and water users	Preparation Training, support to data collection	1-2 months	List of BCWUAs to be formed in each IWMD
Establishment	To establish BCWUAs	Establishment Training Support to BCWUA establishment	4-5 months	Elected Board on each BCWUA, MOUs signed with MWRI
Activation	To strengthen BCWUAs and build partnership with IWMD staff	Activation training Support to IWMD-BCWUA communication, regular coordination meetings Support to joint planning (BC priorities, BC Action Plans)	5-7 months	Internal Regulations, BC priorities, and BC action plans developed by BCWUAs
Participatory Water Management (PWM)	To engage BCWUAs in identifying and carrying out PWM activities	PWM training Support to PWM activities	Ongoing	BCWUAs bring tangible benefits to their members

Five **formal training** activities support this process:

Training	Training modules/topics
Introduction Workshop for IWMD managers (2 days)	BCWUA benefits, formation process, WA staff selection and management
Preparation Workshop for IWMD-WA staff (2 days)	BCWUA benefits, formation process, field data collection, canal grouping
Establishment Workshop for IWMD-WA staff (2 days)	WU communication and awareness, identification of representatives, Board elections
Activation Workshop for IWMD-WA staff (3 days)	Internal Regulations, Principles and practice of Participatory Needs Assessments and Participatory Planning
PWM Workshop for IWMD staff (3 days)	Principles of PWM, PWM applied to water distribution, network maintenance, water quality; organization and administration

These training courses target mostly IWMD staff and provide them with the background, procedures, and tools to establish, activate and empower BCWUAs. Trainers are staff from the MWRI (mostly from the MWRI-IWMU) who are in turn trained and supported by the LIFE-IWRM Project.

An indicative workplan next page details how BCWUAs have been formed within a given IWMD.

Indicative Workplan for forming BCWUAs in one IWMD

Phase	No.	Type of activity	Activity description	Duration	Output	Responsibility
PREPARATION	1	**Workshop/ training**	Introduction Workshop: Awareness and formal training of MWRI managers on process overview and IWMD-WA staff recruitment (WA: Water Advisory)	2 days	Aware IWMD managing staff	IWMU / LIFE
	2	**Field work**	Assignment of IWMD-WA staff	1-2 weeks	IWMD-WA staff assigned	IWMD manager
	3	**Workshop/ training**	Preparation Workshop: Awareness and formal training of IWMD staff on data collection and canal grouping	2 days	Trained IWMD-WA staff	IWMU / LIFE
	4	**Field work**	Data collection	8-12 weeks	Data on all BCs	IWMD-WA staff
	5	**Desk work**	Data review, canal grouping	1-2 weeks	Verified data, list of BCWUAs to be formed	IWMD-WA staff
	6	**Admin work**	**Ministerial decree (one per IWMD) approving list of BCWUAs to be formed**		Official Recognition of the BCWUAs to be formed	MWRI
ESTABLISHMENT	7	**Workshop/ training**	Establishment Workshop: Formal training of IWMD-WA staff on WU awareness, identification of WU representatives and Board elections	2 days	Trained IWMD-WA staff	IWMU / LIFE
	8	**Field work**	WU awareness, identification of WU representatives and Board elections on all other BCs	4-5 months	Elected Boards on all BCs	IWMD-WA staff
	9	**Admin work**	**UnderSecretary decree (one per BCWUA) providing names of BCWUA Board members – MOU between MWRI and BCWUA**		Official MWRI Recognition of the BCWUA	MWRI
ACTIVATION	10	**Workshop/ training**	Activation Workshop: Formal training of IWMD staff on participatory needs assessment, action plans and MOUs	2 days	Trained IWMD-WA staff	IWMU / LIFE
	11	**Field work**	Facilitation of participatory needs assessments and action plans on all BCs	5-7 months	Approved APs on all BCs	IWMD-WA staff
PWM	12	**Workshop/ training**	PWM Workshop: Formal training of IWMD staff on participatory water management activities, procedures and outputs	3 days	Trained IWMD staff	IWMU / LIFE
	13	**Field work**	Involvement of BCWUAs in PWM activities.	Continuing	Tangible results and success stories	IWMD staff

PORTRAIT OF A BCWUA

Each BCWUA involves all water users on the area served by a branch canal, a sub-branch canal or a reach of a (large) branch canal. Besides commonality (same water source), and consideration for the social context (existence of long-term conflicts between neighboring communities), the key criterion in delineating BCWUAs was to ensure some size homogeneity. Achieving the right size is a balancing act as bigger associations:

- Are difficult to manage as democratic transparent organizations, with direct communications between water users and their representatives;
- Risk breaking up into sub-groups, based on communities, villages, canal reaches or sub-branches;

while small associations:

- Have less leverage and credibility; and
- Get less attention from MWRI staff.

Consequently each BCWUA covers from 700 to 4000 feddans (1 feddan = 1 acre), and engages a few hundreds up to two thousands or so water users. Organically, each BCWUA involves:

- 15-50 Water User Representatives (one or two per mesqa or turnout, i.e. per 50-300 feddans); each represents about 10-50 farmers, and selected through a cooptation process (in the future formal elections would be recommended); some representatives are also selected among residents to represent non-farming water users, these usually being women to promote gender equity; collectively these WURs form a type of representative assembly which:
  - Elect and dismiss Board members;
  - Assist the Board in data collection, communications with BCWUA members, and for specific activities (through committees when needed);
  - Collect needs, concerns and priorities from water users and integrate these in the decision-making regarding BCWUA activities;
  - Approve annual reports, action plans (and possibly budgets); and
  - Check and audit Board activities.
- Five to nine Board members: these are elected by the WURs, led by a chairperson, and represent the executive head of the BCWUA; the Board is mandated to:
  - Mediate and resolve irrigation, drainage and water conflicts between BCWUA members;
  - Collect and integrate BCWUA members' needs, complaints, requests and priorities;
  - Lead the preparation of BCWUA documents such as needs assessments and action plans, lead and monitor their implementation;
  - Regularly meet with IWMD staff to discuss water management issues, evaluate solutions, decide and plan activities;
  - Negotiate and conclude agreements with MWRI for the supply of irrigation, drainage and water services and the implementation of related activities;

- Formally or informally report to WURs and BCWUA members at large on Board activities;
- Hold regular (preferably monthly) Board meetings;
- Hold at least one annual meeting with all WURs; and
- Manage external relations, notably with MWRI, other ministries, and local government entities.

Each BCWUA is internally regulated through their own set of Internal Regulations which includes the following topics:

- General provisions (name of BCWUA, legal references, communication rules, membership);
- Structure, procedures for establishment and operating rules (identification and roles of base units and WURs, constitution and responsibilities of the Board); and
- Administration, record-keeping, etc.

WHY BRANCH CANAL WUAS?

Experience shows that the branch canal is the most suitable entry level for establishing sustainable water user associations in Egypt. Branch canals are where MWRI managers and farmers interact: while mesqas are private property and managed by farmers, branch canals are the responsibility of the MWRI. MWRI engineers' chief responsibility is to ensure that branch canals get properly supplied, with water levels high enough for all mesqa intakes to be in turn supplied.

A BCWUA engages several hundred water users over a few thousand feddans and is thus the right compromise size-wise to ensure good communications with water users on one hand, and credibility with the MWRI and other stakeholders on the other.

Forming mesqa-level WUAs is not economically justified since only a few dozens farmers would be involved in each association. Such associations have limited resources and thus impacts, and their small size does not allow them to achieve credibility and partner with stakeholders even at local level. It is interesting to note that while BCWUAs can solve mesqa-level issues, the mechanisms of conflict resolution and participatory water management developed at branch canal level can easily be transposed at mesqa-level and applied even on an informal basis. The MWRI has only been facilitating the formation of mesqa WUAs in the areas of implementation of the Irrigation Improvement Projects (IIP), in order to allow mesqa structural improvement.

Likewise forming mega-associations at district level might be premature in a country where local leaders have limited experience of accountability and transparency. A district-level WUA would have serious difficulties communicating with the thousands of farmers in the district. It may also raise high expectations that may not get fulfilled.

RESULTS AND SUCCESS STORIES

The initial step was the establishment of 27 IWMDs over 5 entire Directorates (covering 1.2 M feddans or 15% of Egypt's irrigated area). Within less than two years, 20 to 35 BCWUAs were then formed in each IWMD, for a total of about 600 BCWUAs involving over half a million water users (mostly farmers).

All these BCWUAs have signed MOUs with the MWRI, and have approved Internal Regulations. Most of them have prepared annual priorities and started collaborating with IWMD staff to address these priorities (through water monitoring or maintenance activities, awareness raising, mobilization of water users, etc.).

About two hundred BCWUAs have also developed annual action plans, focusing on one or two activities to be implemented directly by water users with or without support from MWRI staff.

Regular meetings are held by IWMD staff:

- Individual meetings once every three months or so for one or several neighboring BCWUA Boards to discuss branch canal issues, water user complaints, violations of water structures and waterways, water quality concerns, etc.
- Seasonal meetings twice a year with all chairpersons within the IWMD to discuss district-level (or main canal/drain) issues; this is also an opportunity for:
    - The IWMD manager to reflect on the past season issues and achievements, introduce distribution and maintenance schedules for the oncoming season, discuss these with chairpersons, and pro-actively address potential issues and conflicts; and
    - BCWUA chairpersons to present general water users concerns and priorities, and share achievements/success stories and challenges from their BCWUA.

Among the significant outputs from the involvement of BCWUAs, is a marked decrease of recorded complaints from water users, as well as an improved handling of violations (tampering with water structures or canal banks, illegal constructions, illegal releases or withdrawals, etc.). Violations used to be recorded by MWRI staff and after a couple of warnings, referred to the police for follow-up (follow-up being rare but potentially violent). Nowadays, violations are discussed with Board members, solutions facilitated to the satisfaction of all parties involved. Increased awareness also prevents the occurrence of such violations.

Among other successful outputs, dozens of BCWUA success stories have been collected by the MWRI IWMU and Water Communication Unit (WCU). Some of these refer to the collection of money among water users to handle small-scale repairs or maintenance works to complement or supplement MWRI activities. Voluntary labor also occurred in some branch canals, mostly for de-weeding purposes. Sizeable lengths of branch canals were cleaned from garbage disposal or violations such as tree planting through collaboration between BCWUAs and IWMD staff. Conflicts and disputes among water users have been mediated and solved by BCWUA Boards with limited or no involvement from IWMD staff.

The WCU has been preparing a quarterly newsletter with the most representative success stories. This newsletter is distributed to all IWMDs and BCWUAs supported by the project but also to MWRI staff at large and notably all (200 or so) irrigation districts in Egypt.

Beyond the empowerment of BCWUAs, another significant achievement is the general recognition within the MWRI of the many benefits of WUP. It is also noteworthy that some MWRI engineers (notably from the IWMU) have built a tremendous expertise in how to mobilize and involve water users. These engineers have become in fact the champions of WUP.

PENDING ISSUES

Even if the formation of BCWUAs has achieved impressive results, some issues remain. The most significant one is that BCWUAs lack strong legal recognition. They cannot for example open bank accounts or collect fees from their members, as do officially registered NGOs. They are acknowledged by the MWRI with decrees instructing all MWRI staff to collaborate with Board members and defining respective roles and responsibilities. Similarly BCWUA Internal Regulations are more guidelines than legally binding by-laws, even if approved by the MWRI.

As often the development of the proper regulatory framework (hopefully) follows real activities and achievements. The lack of strong legal backing has not hindered the establishment and involvement of BCWUAs:

- Board members are able to take decisions and enforce them within BCWUAs (they are usually local elders whose new “position” strengthens as mediators, and leaders);
- Peer pressure is an efficient tool to compel violators to change their behavior;
- Most water users know about the existence of the BCWUA and now refer issues, questions and concerns to Board members and not IWMD staff; and
- BCWUAs are considered serious partners by other stakeholders such as the Ministry of Agriculture and Local Councils.

At this point, the process is still fragile and sustainability rests on the implementation of more participatory water management activities to establish the credibility of BCWUAs through tangible results and concrete benefits for water users.

Another issue is the effective involvement of all water users:

- Not all farmers are engaged in BCWUAs (usually 80 to 90% per IWMD); not involved are farmers who directly irrigate from main canals (through pumps or illegal diversions), and farmers farming unofficial lands (desert fringes, non-agricultural lands, etc.);
- To a large extent, BCWUA representatives are almost exclusively farmers; while irrigation is by far the largest use of water in Egypt (about 85%), major impacts on water quality are caused by urban and industrial activities; relevant types of water users will have to be involved; and
- Women are not much involved as they tend to be remotely involved in farming activities (only destitute families allow women to farm).

As mentioned earlier, gender equity is promoted through the selection of women as representing non-farming (resident) water users. There is growing awareness among farmer representatives of the need to involve women: as an example, garbage dumping in canals is a general concern. Awareness activities to prevent dumping have to proceed from household to household and target women. Only women WURs and Board members can carry out such activities and visit other women.

NEXT STEPS

Established BCWUAs are still fragile. The most essential challenge for sustainability is to build credibility. This can only be achieved if they are able to produce concrete results and provide tangible benefits to their members. In order to enhance the self-confidence of BCWUAs, the IWMU has started promoting a set of participatory water management (PWM) activities.

These PWM activities are grouped under four themes and cover most of the basic water management activities at district-level. Each activity should produce a specific output:

Topic		Activities	Outputs
A-Maintenance	A1	Needs assessment, BC priorities and action planning	Action Plan
	A2	Direct work activities (weed removal, manual bank repair, etc.)	BC improvements
	A3	Monitoring of contractor's activities	Field visit reports, tripartite meetings (contractor, WUs, IWMD)
B-Operations	B1	Monitoring of water levels/gate operations on branch canal	Records
	B2	Water allocation among mesqas	Operational Plan - Schedule/calendar
	B3	Data collection/verification re cropping patterns and water needs (MISD)	Crop data
C-Organization/ Communications/ Awareness	C1	Internal communications/ conflict resolution	Internal Regulations (internal meetings)
	C2	Formal BC dialogue with IWMD	Formal BCWUA meetings
	C3	Formal dialogue at district-level	Formal seasonal meetings
	C4	Administrative/Organizational	Records
D-Water Quality	D1	Activities to manage liquid waste disposal	Waste management activities implemented (through Action Plan)
	D2	Activities to manage solid waste disposal	
	D3	Awareness activities regarding pollution	Awareness meetings/actions

These activities will be implemented under the same overall approach that heavily relies on IWMD staff to support and engage BCWUAs. To that end and to nurture the IWMD-BCWUA partnership, benefits for both sides have been identified for each activity:

Topic	Activities	Benefits to IWMD/MWRI	Benefits to WUs
A-Maintenance			
	Needs assessment, BC priorities and action planning	Assists identification of water management needs (distribution maintenance, rehab/improvement etc.), improves efficiency of budget allocation	Achieves concrete results, better addresses WU needs, helps establish credibility of BCWUA
	Direct work activities (weed removal, manual bank maintenance, etc.)	Reduces maintenance costs, improves water delivery	Improves water delivery, complements maintenance by MWRI
	Monitoring of contractor's activities	Transfers part of burden of ensuring work quality	Improves work quality on branch canal
B-Operations			
	Monitoring of water levels/gate operations on branch canal	Improves water delivery, provides performance feedback	Provides better information/ understanding of water availability
	Water allocation among mesqas	Assists with implementation of rotation - Reduces complaints at mesqa level - Increases water use efficiency	Increases equity (increased tail-end availability ?) - Decreases conflicts
	Data collection/ verification re cropping patterns and water needs (MISD)	Provides critical data to improve water delivery, water use efficiency	Improves water delivery (timing/quantities)
C-Organization/ Communications/ Awareness			
	Internal communications/ conflict resolution	Strengthens BCWUAs, solves water disputes, reduces no of violations/ complaints	Provides framework for functioning of association - solving internal conflicts
	Formal BC dialogue with IWMD	Streamlines communications with WUs - reduces no of farmers coming to IWMD, integrates requests/complaints - also provides conduit for awareness raising	Clear access to MWRI-IWMD
	Formal dialogue at district-level		Opportunity to discuss district-level issues with MWRI-IWMD
	Administrative/Organizational	Strengthens BCWUAs as sustainable partners	Provides transparency and accountability
D-Water Quality			
	Activities to manage liquid waste disposal	Complements MWRI awareness activities, improves water quality	Improves water quality, environment, health
	Activities to manage solid waste disposal		
	Awareness activities regarding pollution		

While each BCWUA is encouraged to carry out all the activities, it is up to water users and their representatives to decide which activities are needed, which ones are priorities, and which ones, if any, are not needed (at least for now). On the other hand, other activities not envisioned here can be carried out by BCWUAs as long as these activities are legal and contribute to improving water management.

Beyond building the credibility of the practice of water user participation, the objective is also to encourage a feeling of stewardship among water users. So that they evolve from being passive requesters/beneficiaries to becoming responsible actors. This would be an essential step on the long road towards Irrigation Management Transfer (IMT).

CONCLUSIONS

The conventional approach to form WUAs is to focus on water users. It involves:

- Mobilizing water users (mostly farmers);
- Sensitizing them to the concept and tools of water user participation;
- Leading them through the procedures of establishing and managing their own association (making clear it is non-governmental);
- Building their capacity to operate and manage their system; and
- Actually transferring responsibilities to them (technical, managerial and/or financial).

The main shortcoming of this approach is that governmental water managers are remotely involved and only at central or regional levels. These officials collaborate with the technical specialists or consultants assisting the formation of WUAs, and eventually coordinate with the WUAs for the supply of bulk water resources, the collection of water fees, etc. In the meantime local governmental staff is frequently bypassed and ignored, and quickly perceives the development of WUAs as a way to replace them. The end result is the strong opposition from local staff to water user participation. This is sometimes mitigated by the conversion of local staff into farmers and members of the WUAs (with frequently technical or managerial responsibilities).

The entire process, from awareness raising to actual O&M transfer, can be quite rapid (a few years). Donors tend to push for this approach as it fits within their 4-5 year project cycles. In countries like in Central Asia, the collapse of the Soviet system and the lack of public funds has led governments to adopt this approach (as a way to get rid of costly and derelict assets). But the transition can be quite traumatic for water users (left with significant O&M responsibilities, but limited experience, skills and resources) This approach has sometimes been referred as the “big-bang” approach. It seems to be somewhat successful in India. It has been successful in other countries such as Ecuador where irrigation systems are small and easily managed by water users.

As mentioned before, the initial WUA experiences in Egypt followed the conventional approach, with limited involvement of MWRI local staff, and the assumption that farmers would eventually take over. But Egypt, not unlike Central Asia, is characterized by a:

- Strong and autocratic centralization of decision-making processes;

- Large public sector with plethoric staff notably at field level;
- General lack of initiative-taking from farmers who expect a lot, if not all, from the government (the Nasser period gave Egypt a strong taste of socialism, which the Egyptian bureaucracy has been perpetuating ever since);
- Lack of financial resources (to maintain large water structures) among small-scale farmers; and
- Large irrigation system(s): the Nile Valley (or at least the Delta) is simply one large (and complex) irrigation system; no part can be managed independently.

For these reasons, the conventional “big-bang” approach is unsustainable and may even be counterproductive. Moreover, and unlike Central Asia, water user participation in Egypt also has to operate with an unsupportive regulatory framework: BCWUAs can not yet register as NGOs and are not allowed for example to collect fees.

The approach followed by the MWRI with technical assistance from the LIFE-IWRM Project focuses on empowering water users while building a strong partnership with IWMD staff. It is through that partnership that actual issues are tackled and tangible benefits achieved, in terms of improved allocation of water resources and O&M funds, better resolution of water disputes, etc.

This approach also creates the conditions for a successful dialogue between managers and users, builds the confidence of water users and eventually paves the way for an incremental evolution towards an Egyptian-type of Irrigation Management Transfer. Complementarity is the key for a smooth, gradual transfer of irrigation and drainage O&M responsibilities.

REFERENCES

Eng. Nabil Fawzy, Eng. Maher Khodary, Viala E., *Integrating Water Management in Egypt: from concept to reality* (paper presented at USCID Water Management Conference in Boise, Idaho, October 2006)

THE MAN SWIMMING AGAINST THE STREAM KNOWS THE STRENGTH OF IT

HYDRAULICS AND SOCIAL RELATIONS IN AN ARGENTINEAN IRRIGATION SYSTEM

Maurits W. Ertsen[1]
Ronald van Nooijen[2]
Bas van Son[3]

ABSTRACT

In this paper we discuss hydraulic behavior of irrigation infrastructure within a context of spatially distributed power relations in an Argentinean irrigation system. In the Río Dulce basin the irrigation area known as the Proyecto Río Dulce (PRD, command area 350,000 hectares) is the main irrigated area . An interesting characteristic of the PRD is that the larger landowners are mainly situated in tail end areas. Despite this potentially disadvantageous position, downstream farmers do not encounter problems. This should not be regarded as self-evident: the hydraulic properties of the canals induce a need for downstream farmers to take deliberate action to ensure proper water delivery to their farms. When upstream farmers do not irrigate, too much water can flow downstream; when they irrigate too much, or manipulate cross regulators, downstream water scarcity can be the result; when canals are not maintained, extensive plant growth will increase hydraulic resistance and decrease discharges. It is not a coincidence that the downstream farmers invest heavily in canal maintenance. These investments appear to be appropriate, as larger farmers tend to irrigate much more on average compared to the smaller farmers upstream.

INTRODUCTION

The best known debate on power and irrigation was born from studying the formation of the ancient civilizations. Most of these are located in hydrologically distressed regions, usually arid plains with a single (rain dependent) large river running through them. Within such an agricultural landscape, water is the natural variable par excellence. Irrigation has played a crucial role in cultural development, and in the formation of these states. In the (semi-)arid regions of early civilizations with their large rivers water is not only highly mobile, but also quite bulky. This bulkiness relates to mass organization; as such a large quantity of water is supposed to be channeled and kept within bounds only by the use of mass labor. Although he was certainly not the first to stress the importance of irrigation and water control in societal

[1] Senior lecturer - Water Resources , Department of Civil Engineering and Geosciences, Delft University of Technology, PO Box 5048, 2600 GA Delft, the Netherlands. Tel + 31 (0) 15 27 87423, Fax + 31 (0) 15 27 85559 m.w.ertsen@tudelft.nl
[2] Senior lecturer - Water Resources , Department of Civil Engineering and Geosciences, Delft University of Technology, PO Box 5048, 2600 GA Delft, the Netherlands. Tel + 31 (0) 15 27 87423, Fax + 31 (0) 15 27 85559, r.r.p.vannooyen@tudelft.nl
[3] Student - Hydraulic Engineering, Department of Civil Engineering and Geosciences, Delft University of Technology, PO Box 5048, 2600 GA Delft, the Netherlands. Tel + 31 (0) 15 27 87423, Fax + 31 (0) 15 27 85559 basvanson@gmail.com

development, Wittfogel was the first to develop a general theory about this importance. A crucial argument of Wittfogel (1957) is that the required mass labor must be coordinated and disciplined: it must subordinate itself to a directing authority. Small-scale irrigation farming involves a high intensity of cultivation on irrigated fields too, but Wittfogel preserves central control for situations when large quantities of water have to be manipulated. Up to today, many scholars studying development of large irrigation works assume, in the spirit of Wittfogel, that these irrigation works always were constructed in one phase, requiring a strong institution (a central state) to supervise and organize such massive work. It is quite likely, however, that larger systems are the result of many smaller scale actions in a longer time period (Ur 2002). Furthermore, "large scale" does not necessarily mean "strong central authority" (Hunt and Hunt 1976; Hunt 1988).

In such processes of many smaller scale actions, irrigation systems are both result of actions and the (material) context of new actions. Developing (and managing) irrigation infrastructure is a social practice; irrigation (infra)structures become concrete through human action in (continuous) use, design and construction. Actions and infrastructure together create spatial and temporal patterns of water flows, which are very likely to provoke new actions on either individual and/or collective level, which are constrained by hydraulic properties, and other factors. We argue that hydraulic infrastructure in irrigation systems can be conceptualized as structures as Giddens defines them: structures are medium and outcome of social practices through everyday actions, in which routines are an important phenomenon (Giddens 1984; 25). Structures like irrigation systems become concrete through human action in (continuous) use, design and construction. Canals and other objects set the material and spatial reality, within which social interaction shapes spatial patterns of water flows and related actions through time. An important issue in irrigation related to water control is the nature of unstable water availability during seasons and over the years. Many rivers have an irregular flow pattern, with large fluctuations in and over seasons and very low flows in the dry season. It is precisely this unpredictability which has been the drive for major changes in the Río Dulce irrigated area in Argentina discussed in this paper.

Our paper shows that large-scale irrigation development in this semi-arid area with its one major river needs to be understood in terms of series of actions by smaller groups of stakeholders within a context of changing positions of central state authority. All this has not resulted in stronger central management; within the process, several groups from state institutions and irrigators competed over water control. It should not be a surprise that, given that in human society control of knowledge, possessions and power is skewed, the outcome of this competition is socially stratified too. In many irrigation systems, as in the Río Dulce area, water is unevenly allocated. Water management roles are actually power roles, which are directly linked to control of production. To control flows of water, or in other words to be(come) powerful, resources need to be enrolled, like canals and division boxes. Social relationships are re(shaped) and changed when agents struggle with and upon artefacts (Van der Zaag 1993). Power is not something hidden, negative or obscure; it is expressed daily in the capacity to achieve outcomes successfully through enrolment of resources (Giddens 1984). Some irrigators have managed to increase their control over irrigation water flows. We will show in this paper that this increase is not something which has to be taken as granted. The hydraulic reality of the irrigation system requires continuous efforts from some irrigators to maintain (let alone increase) their control.

To develop and substantiate our argument further, we will start with discussing the development process of and water use patterns in the Río Dulce irrigation area. These two paragraphs will be followed by a description of the Canal San Martin, our main case study linking hydraulics and power. Then we will explain our modeling approach and present our results. The paper will be closed with a discussion, in which we will elaborate on some considerations for understanding power relations in irrigation.

HISTORY OF THE PROYECTO RÍO DULCE, ARGENTINA

In the Río Dulce basin, Argentina, irrigation is the main water user and consequently providing water for irrigation has been one of the main goals for activities in the basin. The basin is small in relative terms (rough estimation: about 100,000 km^2). The importance of irrigation in the basin makes it an excellent case to discuss (some) possibilities of using historical studies to evaluate and appreciate the meaning of irrigation in a river basin. Within the Río Dulce basin, the irrigation area known as the Proyecto Río Dulce (PRD, irrigable area 122,000 hectares in a command area of around 350,000 hectares) has an immense influence on the catchment water balance in absolute and relative terms. A total of 122,000 hectares has water rights, about 50,000 have been irrigated in the last two decades; about 100,000 hectares are irrigated in recent years. Before 1968, the irrigation infrastructure provided two or three irrigation turns for each farmer in late spring and summer, when the water levels in the Río Dulce were sufficiently high. The building of a reservoir in 1968, the Embalse de Río Hondo, has shaped the potential for irrigation all year round. Discussing the history of the system will show how sizes and directions of water flows have been changing by human interference, and how these have influenced the behavior of the system at different scales.

The province of Santiago del Estero counts 150,000 square kilometers, inhabited by a little over 800,000 people. The climate of the Gran Chaco, of which Santiago del Estero forms the western border, is continental: winters are relatively cold and summers are hot. Annual precipitation, mainly summer rains (November-April) ranges from 500 mm to 850 mm, with winters being almost totally dry. In this dry and remote landscape two rivers are searching their way to the sea. Although small in comparison to Argentina's major river the Río Parana, these two rivers are the vital sources for life in Santiago del Estero. Along these rivers agricultural and pastoral activities have been the foundation for the economy of Santiago. One of them, the Río Salado has succeeded in reaching the Río Parana. The other river, the Río Dulce flows into the salt-lake La Mar Chiquita. In 1577, the Spanish built their first irrigation ditch (*acequia*) in Santiago del Estero. In 1583 this reached a length of 5 kilometers. The Río Dulce repeatedly destroyed the original ditch, until in 1650 a permanent canal was constructed. In 1680 an irrigator’s register was established. Many individual landowners dug a ditch until they reached their land. This is part of the explanation why the larger landowners (still) are situated in many tail end areas: they automatically became tail-enders, as their canals ended on their lands. The map of the irrigated area shows that in modern times larger landowners are still situated in the downstream areas (figure 1). In 1873, 73 acequias existed. These canals were not the small ditches one would perhaps expect: most were longer than 10 kilometers, some extending even up to 50 kilometers with a width of 6 meters. Official records indicate that about 8,000 hectares were irrigated by the acequias, but in practice this figure would have been higher (Michaud 1942).

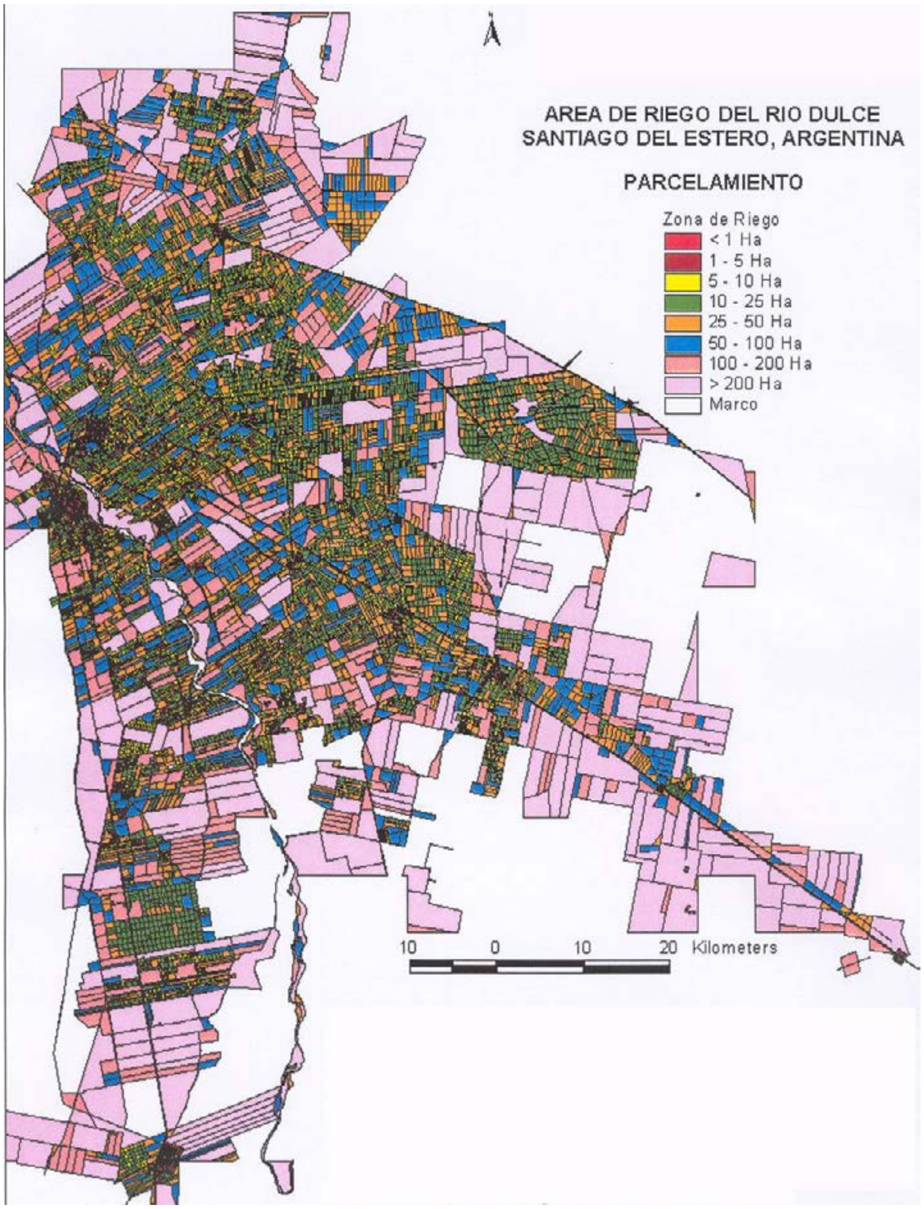


Figure 1. Land distribution in the Río Dulce area

In 1878 canal *La Cuarteada* was built to pass floodwater from the Río Dulce to the Río Salado (Michaud 1942, Achaval 1988). However, instead of diverting excess water, the canal inundated the land around it. Not before long individual agriculturists began to build their acequias from La Cuarteada, thus changing a canal basically built for flood control (drainage) into an irrigation canal. In 1886 an intake structure was constructed for La Cuarteada (Michaud 1942, Achaval 1988). In addition, a program to develop the irrigated area by building more acequias in the command area of La Cuarteada was formulated. The intake structure did not hold long; the Dulce River washed it away. As the agricultural interests in the area had grown, plans were made to build a new structure. The new intake came in use in 1898 (HARZA 1965). Massé (1906) calls this structure the largest intake in Argentina of those days. In 1905 the existing irrigation infrastructure was further extended. From then on, the intake diverted water to a main canal, at the end of which (*La Darsena*) *Canal Norte*, *Canal Sud* and Canal La Cuarteada branched off (Michaud 1942). This was the first public irrigation system in Santiago del Estero. It has become the basis for the existing infrastructure on the left bank of the modern Proyecto Río Dulce. It irrigated about 38,500 hectares; 14,500 hectares were irrigated from private acequias (HARZA 1965). In 1913 a communal canal on the right bank was constructed, *Canal San Martín*, with a length of 64 kilometers (Michaud 1942).

The canal systems on both banks derived water when flow and water level of the river was sufficiently high. The diversion dams in the river (*diques de ramas*) collapsed when discharges were very high. Water derivation could hardly be regulated, since no storage was available. Water was usually (sometimes too) abundantly available in the wet season (December-April), but scarce in the dry period (*estiaje*) (July-October). Farmers had to make use of the start of the rainy season (November/December) to prepare their lands and sow their crops. During the rainy summer, one or two irrigation turns were usually available, but water availability and thus the number of turns changed from year to year. Due to this insecurity of the water supply, farmers never could be completely sure of receiving sufficient water to grow their crops. Alfalfa (grown at about 12,700 hectares) and maize (about 10,000 hectares) were important crops, together with cotton (about 9,000 hectares) (Michaud 1942). Most farms were relatively small: on the left bank, more than 1,000 farms (of a total of nearly 2,000) were between 1 and 5 hectares, where only 9 were more than 100 hectares (Michaud 1942). Around 1923, many European farmers arrived in Santiago, resulting in a sharp increase in the amount of irrigated hectares, with a clear decrease of available water per hectare as a result. According to normal irrigation practice in the area these farmers received water at the end of an irrigation turn. Soon they realized that irrigation water availability was not enough to sustain the needs; farmer representatives approached the Provincial Government and later the National Government to employ works to increase the amount of water (Prieto 2006). In 1947 the federal organization for water affairs *Agua y Energía Eléctrica* (AyEE) began to build a permanent diversion weir in the river, the *Dique Los Quiroga* (Gastaminza 1989, Michaud 1942).

At first, the main canal fed by Los Quiroga, *La Matriz*, only diverted water to the La Cuarteada system. San Martín continued to derive water directly from the river, as did the remaining private acequias. However, these canals downstream of Los Quiroga had difficulties getting water, in particular during periods of low flow. Most of the flow was diverted to the La Cuarteada system on the left bank. Again, assistance from the National Government was looked for. As a solution, the San Martín system was connected to La Matriz through a siphon around 1954 (Prieto 2006). Some private acequias remained in the San Martin area, but they did not take water directly from the river any more; they were connected to the San Martín network. The main reason for the owners of the acequias to agree with this arrangement was that it secured their water delivery. It has not been possible to determine in detail how Los Quiroga has influenced water availability, as data are not available. Although water availability would have increased (as the issues in the San Martín area indicate), it is highly unlikely that the increase has reversed the sharp decrease of water availability in l/s/ha sketched. Given the uneven distribution between left and right banks, it is possible that the left bank did have an increased water availability (the irrigated area increased relatively more in that area), where the right bank canals saw their water availability decrease (Prieto 2006).

Overall water availability was to be improved by a reservoir in northwest Santiago, the *Embalse del Río Hondo*. AyEE presented plans in 1957 and the reservoir was completed in 1968 (Gastaminza 1989). The reservoir has shaped the potential for irrigation all year round. However, its capacity is insufficient to provide more than annual regulation. Consequently, in a year with less than average rainfall, the reservoir cannot fully meet the diversion requirements for the total irrigable area. In 1966 the Proyecto Río Dulce was formulated (Gastaminza 1989). New canals were to be constructed, old canals rehabilitated and the acequia system was to be replaced by a tertiary unit system. Activities could not be extended to all the irrigated areas of the PRD. Two existing areas (parts of the former La Darsena system and the Canal San Martin) and one new area (Colonia Simbolar) can be considered modernized, with the remaining (larger) area virtually unchanged. The three development phases of the relationship between water, engineering and landscape described by Petts (1990), although probably too simple, are illustrative for developments in Santiago del Estero. The first phase, management of perennial water sources for local agriculture and domestic supplies and the opportunistic use of seasonal floods and rains for agriculture, extends until about 1870 in Santiago del Estero. The second phase, involving the management of rivers for waterpower, informal regulation of seasonal floods for irrigation agriculture and drainage of wetlands can be defined between 1870 and 1968, with 1950 being a first step in the direction of the third phase, during which rivers have been regulated by large structures, often as part of a complex basin or inter-basin development, for hydro-electric power generation, water supply and flood control. In the Río Dulce basin, this period extends from 1968 onwards. Data from the PRD show that inflows per hectare are significantly higher in the third period than in the second period (before Los Quiroga was built) (figure 2). For the period when Los Quiroga was in use we have no data.

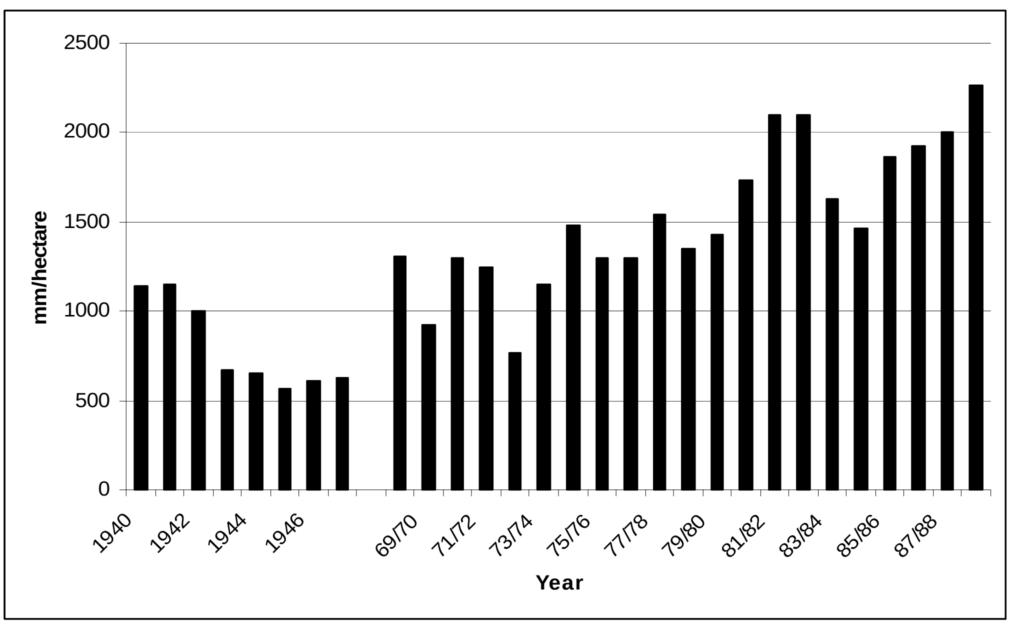


Figure 2. Water use in the PRD (1940 – 1990) (data from Ertsen et al 2004; Prieto et al 1994)

INSTITUTIONS, FARMERS AND WATER MANAGEMENT

To arrange water distribution the Río Dulce irrigated area has known a differentiated pattern of institutional settings for irrigation management throughout its development process. The first irrigation related initiatives were private, in which (groups of) individuals constructed their own canal (sometimes very close parallel to each other). The system of La Darsena, although started with a drainage canal, was an irrigation system, built by federal and managed and controlled by provincial authorities. Further downstream the private acequias were still in use. In 1947 the federal organization for water affairs Agua y Energía Eléctrica (AyEE) was installed (Gastaminza 1989), which had three divisions: construction, water exploitation and energy exploitation. The first division constructed all the works for the other two. One of the first actions of AyEE in Santiago del Estero was the building of a new diversion work, the *Dique Los Quiroga*, connecting La Darsena on the left and San Martin on the other bank and constructing a new main canal, *La Matriz*. In 1964 the *Corporación Río Dulce* (CRD), a working group of the provincial authorities, was established, which should formulate plans in order to stimulate the integrated development of the Río Dulce region (note that the CRD should work in the total catchment of the Dulce river, not just in the Quiroga system). When in 1966 the Proyecto Río Dulce was formulated, the division of work between AyEE and the CRD was that AyEE managed all water affairs (construction, distribution and maintenance) within the PRD and that the CRD was responsible for the socio-economic development of the project.

In 1991 it became clear that because of budget cuts in the federal government Agua y Energía Eléctrica would no longer be responsible (and thus pay) for the PRD management. The irrigation-related tasks of AyEE became the responsibility of the province of Santiago del Estero. The province created the *Unidad Ejecutora del Servicio de Riego del Río Dulce* (UESRRD, in practice UER) (Sosa 1994b, UER). The role of the users in this process was very interesting. Involvement of users in system management was foreseen for the PRD (AyEE 1971, Reglamento 1970), but formal organizations did not exist. General farmer organizations did exist, but these did not interfere in water management as such, as they focused on marketing (especially cotton). This does not mean that producers had no influence on water management. They did, but as individuals. It will not be a surprise that those individuals were the larger farmers[4]. In the situation of unstable co-management between AyEE and the province, which did not secure workable water distribution on the longer term, producer organizations came up. In a relatively short period of time, two new producer organizations were established and two existing ones started to extend their activities to water management. The UER signed agreements with all these organizations. The UER would remain responsible for the main system (Los Quiroga and Matriz), the farmer organizations were responsible for the secondary canal. Resources needed for secondary canal maintenance were given in usufruct to the producers by the UER. The first agreement was signed on the 2d of April 1993 with the *Asociación de Productores Agropecuarios Zona IV*, the farmer organization in the San Martin area, our main case study within the PRD.

---

[4] No written material is available on this more subtle type of influence, but it sometimes happened that bigger farmers paid for repairing canals when AyEE had no resources available. Once a farmer blocked a canal called Jume Esquina (maximum flow 20 m3/s) and diverted it to his fields. He was fined, but he apparently never paid.

As one of the new farmer organizations, the Asociación of Canal San Martin was specifically established to secure water distribution within the canal area. As in the Río Dulce irrigated area as a whole one of the important features of this canal area is that the larger and most powerful farmers can be found in the tail-end of the area. This sets the scene for potentially interesting interaction between the larger farmers in the downstream and the smaller farmers in the upstream parts of the canal. As Van der Zaag puts it "[t]he social relationships between major groups of actors found in an irrigation system are partly structured by the practical experience the respective groups have of coping with the physical infrastructure." (Van der Zaag 1993; 81). Within the context of institutional change in Santiago del Estero the mechanism of appropriation of the canal is especially important. Van der Zaag discusses a case in Mexico, in which farmers took the initiative to collectively clean their canal and construct a better intake. Through investing labor and money they practically appropriated the canal. This is what happened in the San Martin area too. The larger farmers appropriated the canal when in their view the scheme management was unable to guarantee water delivery and maintenance.

The object of appropriation, the canal itself and its associated structures is probably as interesting itself as its socio-spatial context (see figures 3, 4 and 5). Canal San Martin serves an area of about 19,000 hectares, and is the only secondary canal on the right bank of the Rio Dulce. Water is diverted to the canal from the main canal Matriz through a siphon under the river itself. The official capacity of the canal is set at about 10 m^3/s, in practice 5 to 6 m^3/s are diverted into the canal. The total canal grid in the area amounts to about 152 km. Canal San Martin itself is lined for the first 38 km, its total length is a little over 60 km. Apparently the original design anticipated upon demand based irrigation management, as the off-takes in the canal are AVIO gates. The canal itself seems to miss the storage usually associated with downstream control. Furthermore, the lined part of the canal includes three cross regulators in the shape of sliding gates. Each cross regulator has an emergency overflow side weir directly upstream. In daily practice, the AVIO gates are not used at all. The off-takes are managed through a simple open or closed routine, in line with the general distribution pattern described above, in which farmers are allowed to irrigate once a month. The combination of downstream controlled off-takes, upstream controlled canal regulation and side spills would not support demand management easily. Even more interesting is that this hydraulic layout appears to be a potentially large disadvantage for downstream users. Manipulation of cross regulators could easily result in lower discharges downstream, especially since overflows caused by such manipulations would be spilled out of the canal and thus no longer be available for downstream uses.[5]

MODELING CANAL SAN MARTIN

To study the effects of interventions, management actions and hydraulic constraints posed by the canal we modeled the Canal San Martin. As information about cross sections and slopes were not available for the unlined part of the canal we limited our modeling to the first 38 km. It is known that the unlined canal serves a considerable number of (larger) farmers. Therefore, we did check how much water was available immediately downstream of our modeled section. Length

[5] The overflows spill in the drainage canal roughly parallel to the irrigation canal. In fact, the current drainage canal is the old Canal San Martin (unlined). To what extent drainage flows are usable and used downstream is not clear.

profiles and cross sections of the first 38 km were known, as were detailed measurements of the hydraulic structures at the location of the first cross regulator (side spill, intake for Carloz Lopez canal and cross regulator). Carloz Lopez is a canal delivering water to a sub-system of several tertiary units; therefore it continuously draws water up to 3 m^3/s. Measurements of cross regulators 2 and 3 were not available, but we assumed that these were in proportion to cross regulator 1. Measurements of a typical off-take were available. As the AVIO gates are not used, we modeled the off-takes as simple orifices able to deliver the required discharge as defined by the irrigable area downstream of the off-take. With this model several scenarios were simulated. We focused in particular on the influence of canal maintenance, manipulation of cross regulators and setting off-takes. Maintenance of the canal is very important. Officially the whole system is closed for one month per year to clean and repair canals (usually in May). The San Martin is a particular case. Its canal side slopes are lined with concrete slabs; the canal bed is lined with stone blocks. Water plants can easily grow on the canal bed, which they do abundantly. To remove the plants Canal San Martin is emptied during the irrigation season several times. The fierce sun kills the water plants, which are flushed away the next time the canal is operated again.

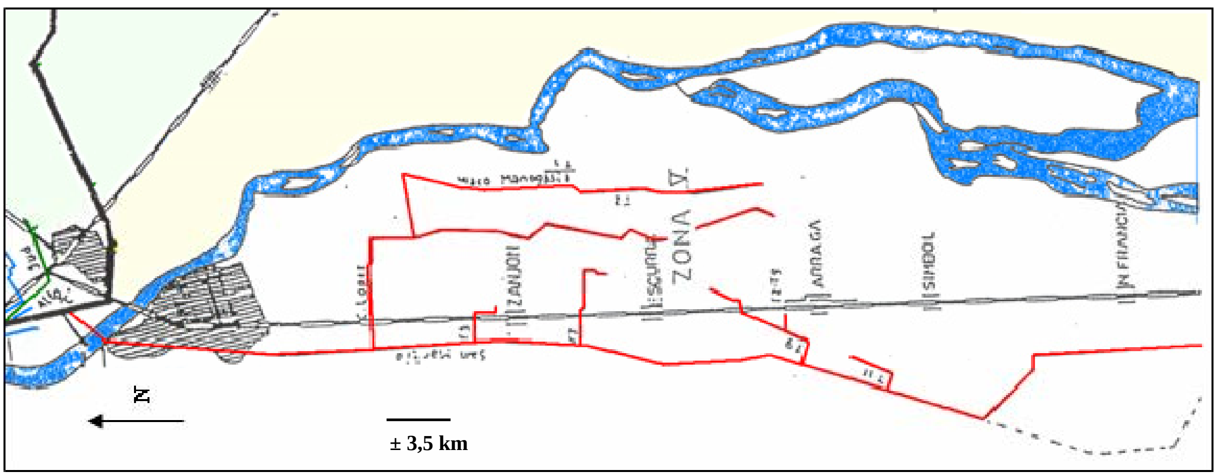


Figure 3. Schematic overview of Canal San Martin

Our first few runs were to estimate 'normal' behavior of the canal. Apparently, the settings of the first side spill are very sensitive. With a water level increase of just a few centimeters above what apparently has been defined as target level, water is spilled in the drainage canal. As we remarked before, the canal seems not to have been designed for storage. We used the Strickler roughness coefficient to tune the canal to the discharges measured in the canal. For a discharge of 5.5 m3/s, which seems to be the normal discharge, the Strickler coefficient would be about 30 $m^{1/3}/s$, which is very low for a lined canal. With a design discharge of around 10 m^3/s, however, obviously the roughness factor would have been higher. The increased roughness caused by vegetation was included in the model by lowering the roughness coefficient to values of 20, 15 and 10 $m^{1/3}/s$, respectively. A lower coefficient obviously results in lower discharges and increased water levels (figure 6). This means that the side spill upstream of the first cross regulator will start to divert water to the drains (0.2 m^3/s, 0.6 m^3/s and 1.5 m^3/s respectively).

These are substantial values, given the target discharge of 5.5 m^3/s.

Figure 4. Impression of the San Martin area from Google Earth

Upper left: San Martin downstream of first cross regulator
Middle left: emergency spill upstream of first cross regulator
Lower left: farm intake from field canal to field

Upper right: first cross regulator
Middle right: tertiary canal
Lower right: typical farm

Figure 5. Images of the Canal San Martin

The water discharged over the side spill only influences availability downstream of this location. Canal maintenance is thus vital for downstream farmers to secure water delivery to their farms. Another way to influence the downstream flow is to manipulate the cross regulators. When the sliding gates of the cross regulators are lowered, downstream discharges (obviously) decrease.

With the sliding gates set at openings of 0.1 m, only 1.5 m^3/s flows through the gates to the downstream users. At the first cross regulator all the excess water is discharged into the drain. Assuming that water users would only manipulate structures in irrigation systems to increase the flow to their own units or fields, we wanted to know if that would be successful. The results show that if upstream users would take their water simultaneously, the exact setting of the cross regulators does not influence downstream flows that much anymore. Furthermore side spill discharges decrease. The simulations clearly show the key role of the configuration at the site of first cross regulator. Basically, the users of the Carloz Lopez canal, which draws considerable volumes from the incoming discharge, could determine water availability for their (larger) colleagues downstream. It is current practice that smaller farmers irrigate their cotton or alfalfa on average three to four times per year and use about two and a half times more water per turn than allowed (240 mm/event). Before the reservoir two or three irrigation turns were available for each farmer in late spring and summer, when water levels in the Río Dulce were sufficiently high. Irrigators were used to handle such larger flows on their relatively large fields (Romanella 1971). Apparently, smaller farmers reproduce the distribution schedule of the unregulated period[6]. Thus, improved water security and control has apparently not changed the water use practices of these farmers much. The larger farmers, with more diversified cropping patterns, do take advantage of the new potential made possible by the reservoir. They combine the irrigation strategy of the smaller farmers (irrigating crops a few times), but take water during 6 to 8 turns because they irrigate only a fraction of the area available to them each turn. They sometimes irrigate a larger area than officially allowed (Prieto 2006). Therefore, it can be concluded that these larger farmers are able to arrange irrigation matters in their favor despite their potentially disadvantaged position in the tail of a canal with a hydraulic behavior favoring upstream users.

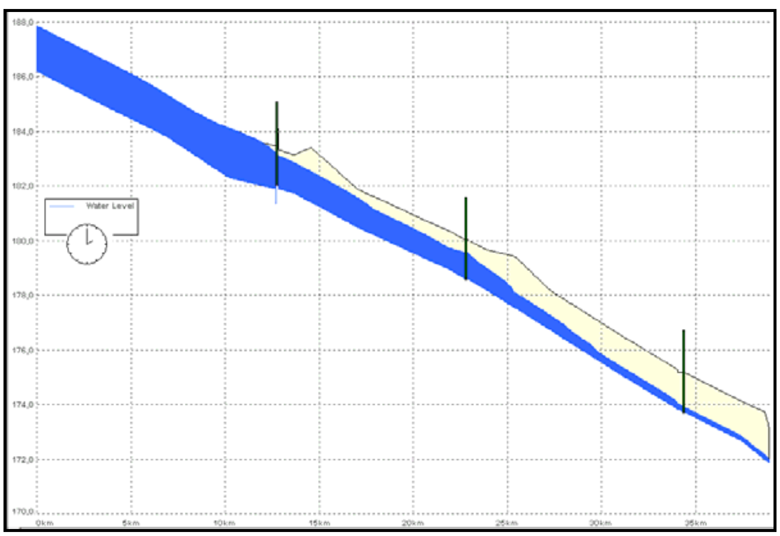


Figure 6. Typical output graph: side view of case with increased roughness in upstream canal stretch. The resulting increase in water levels cause higher side spill discharges and thus a lower flow into the downstream canal stretches

[6] Two main differences may be noticed: the stronger regulation of the available flows allows better-secured starting conditions for the crops and a better regulated growing season; however, the crops grown nowadays respond less well to this distribution than the types grown before.

CONCLUDING REMARKS

In this paper we tried to discuss the relation between social economic context, power relations and irrigation infrastructure. We start from the idea that irrigation systems are assembled from elements into a physical object with a certain form, which orders the space encompassed by these elements into a pattern. Irrigation systems are therefore transformations of space through objects. We argued that the ordering of space in irrigation systems is really about the ordering of relations between people (Hillier and Hanson 1984). Spatial structures like irrigation systems are the material form of social structures and relations. Such a social production of space is socially reproduced in daily actions. We have stressed the structuring role of hydraulic infrastructure in irrigation related power relations. Obviously, we do not want to argue that hydraulics determine the social. We do think, however, that the physical shape of irrigation, including spatial positions of farmers, canal layout and control structures, does matter when trying to understand social relations within irrigation systems.

Our tentative modeling results confirm that the hydraulic design and behavior of Canal San Martin is generally disadvantageous for downstream users. Although the design suggests that demand based management has been one of the considerations, the canal system as a whole cannot materialize this consideration appropriately. That downstream users do make more extensive use of the modernized infrastructure than their upstream smaller colleagues is not strange itself. At the same time, we should not take such a confirmation of what would be expected from social point of view for granted that easily. Powerful as they are, downstream users still need to continuously re-establish their control over the system. These users need to make efforts to maintain their power, for example in the political arena (as in the early 1990's) or within their own canal system (through maintenance). At the same time, these continuous efforts confirm the existing power relations already expressed in land ownership and political influence.

REFERENCES

Achaval J.N. (1988) *Historia de Santiago del Estero: siglos XVI-XIX*, Ediciones Universidad Catolica de Santiago del Estero. Santiago del Estero, Argentina

Ertsen, M.W., Prieto, D., Pradhan, T.M.S. & Angella, G. (2004) *Historical analysis of water flows in the Río Dulce catchment*, Proc. 2nd Asian Regional Conf., Intern. Comm. on Irrig. and Drain., Echuca-Moama, Australia.

Gastaminza E. (1989) El aprovechamiento del río Dulce: su pasado, presente y futuro, *El Liberal*, January 25th 1989, Santiago del Estero, Argentina

Giddens A. (1979) *Central problems in social theory: action, structure and contradiction in social analysis,* Contemporary social theory, MacMillan, London

Giddens A. (1984) *The constitution of society: outline of the theory of structuration*, Polity Press, Cambridge

Harza Engineering Company (1965) *Proyecto Río Dulce. Informe de Factibilidad. Proyecto Río Dulce. Supporting studies to the feasibility report*, Agua y Energía Eléctrica, Buenos Aires, Argentina

Hillier B. and Hanson J. (1984) *The social logic of space*, Cambridge University Press, Cambridge

Hunt R.C. and Hunt E. (1976) Canal irrigation and local social organization, *Current Anthropology* 17(3)

Hunt R. (1988) Size and the structure of authority in canal irrigation systems, *Anthropological Research* 4(44)335-355

Massé J.B. (1906) *Rapport sur la création de Colonies Cotonnièrs Nationales présenté a Son Excellence le Ministre de l'Agriculture Docteur Damián M. Torino*, Ateliers de Publications du Bureau Météorologique, Buenos Aires, Argentina

Michaud C. (1942) *Regadios en Santiago del Estero y en particular en la zona del Río Dulce. Santiago del Estero, Argentina*

Petts G. (1990) Water, engineering and landscape: development, protection and restoration. In: Cosgrove D. and Petts G. (eds) *Water, engineering and landscape. Water control and landscape transformation in the modern period*, Bellhaven Press, London

Prieto D. (2006) *Modernization and the Evolution of Irrigation Practices in the Río Dulce Irrigation Project*, PhD Thesis Wageningen University

Prieto D., Soppe R. and Angella G. (1994) *Efficiencia de uso del agua de riego en el Proyecto del Río Dulce, Santiago del Estero*, 1ras Jornadas Provinciales de Riego, Santiago del Estero, Argentina

Prins U. (1995) *Loosing water or water getting lost in an irrigation labyrinth: irrigation water distribution in the irrigated area of river Diguillin, Chile, seen from different actor perspectives*, MSc-thesis, Department of Irrigation, Wageningen Agricultural University

Romanella C. (1971) *Planificacion del riego en el area del Proyecto del Río Dulce. Informe final*, Agua y Energía Eléctrica, Working document

Soja E. (1985) *The spatiality of social life: towards a transformative retheorisation*, in: Gregory D. and Urry J. (ed)):

Ur J.A. (2002) Settlement and landscape in northern Mesopotamia: the Tell Hamoukar survey 2000-2001, *Akkadica* 123:57-88

Wittfogel K. (1957) *Oriental despotism. A comparative study of total power*, Yale University Press, New Haven

ROLES AND ISSUES OF WATER USERS' ASSOCIATIONS FOR SUSTAINABLE IRRIGATION AND DRAINAGE IN THE KYRGYZ REPUBLIC AND UZBEKISTAN IN CENTRAL ASIA

Koji Kitamura[1]

ABSTRACT

The Kyrgyz Republic, Uzbekistan, Kazakhstan, Tajikistan, and Turkmenistan in the Aral Sea basin in Central Asia have some of the largest irrigation and drainage infrastructure in the world. In the Soviet era, a huge amount of irrigation and drainage infrastructure was constructed by the government, mainly to increase the production of cotton and wheat. However, the irrigation and drainage infrastructure has severely deteriorated since the independence of the Central Asian countries in 1991, mainly due to the lack of necessary funds for operation, maintenance, and rehabilitation. The governments intend to establish and develop water users' associations (WUAs), which are expected to play an important role in operation and maintenance (O&M) of the irrigation and drainage infrastructure. However, the use of WUAs for O&M is quite new in Central Asia. Therefore, the Asian Development Bank, the World Bank, and other donors have been implementing projects not only for the rehabilitation of the deteriorated irrigation and drainage infrastructure, but also for the establishment and development of WUAs. The roles of WUAs for O&M in Central Asia are very important in having an efficient and sustainable irrigation and drainage system. The roles and issues facing WUAs in the Kyrgyz Republic, which has adopted a rapid approach to reform, and Uzbekistan, which has taken a gradual approach, were reviewed in this study.

INTRODUCTION AND BACKGROUND

Introduction

The Aral Sea basin in Central Asia contains five countries: the Kyrgyz Republic, Uzbekistan, Kazakhstan, Tajikistan, and Turkmenistan. These countries became independent in 1991 with the collapse of the former Soviet Union. The region is expected to experience rapid economic development in the near future because it has abundant natural resources such as petroleum, natural gas, and various rare metals.

The annual precipitation in Central Asia is extremely limited, ranging between 50 mm and 600 mm, and more than half of the region is desert. Traditionally, the people of Central Asia made a living by raising sheep, horses, and camels either in the vast areas as nomads or locally by using irrigated agriculture in river basins and areas of oasis. However, the lifestyle and land use changed drastically after the area was annexed by the Soviet Union. Under the planned economy of the Soviet Union, the agricultural lifestyle shifted from nomadism to settlement.

Large-scale irrigation and drainage infrastructure was introduced in the 1940s in order to

[1]Senior Researcher; National Institute for Rural Engineering; 2-1-6 Kannondai, Tsukuba, Ibaraki, 305-8609, Japan; kojikita@affrc.go.jp

increase agricultural production in the region. By the late 1980s, more than 7.5 million ha of land in Central Asia were irrigated, mainly for the production of cotton and wheat. The irrigated areas are distributed along the Syr Darya and Amu Darya Rivers (Fig. 1), which are the primary source of the water used for irrigation although groundwater is also used. Because the two rivers empty into the Aral Sea, the Aral Sea has become smaller as a result of the diversion of river water for irrigation.

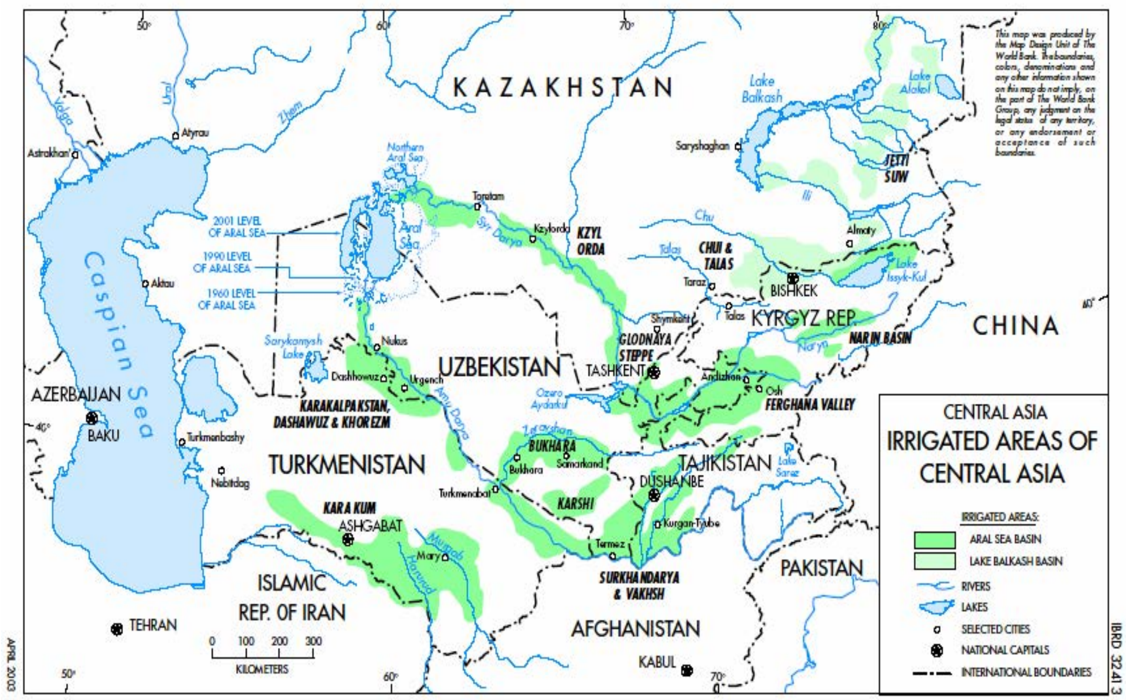


Figure 1. Irrigated Areas of Central Asia (World Bank, 2003)

The irrigation and drainage infrastructure has been rapidly deteriorating since the independence of the countries (Fig. 2). The main reason for the deterioration is the lack of governmental funds and human resources necessary for the operation, maintenance, and rehabilitation of the infrastructure. Farm productivity and farm income have seriously decreased as a result of this deterioration, as well as because the agricultural sector has been changing from a planned economy to a market economy.

Because irrigation and drainage are very important for improving agricultural productivity and alleviating farmers' poverty, the governments have decided to introduce a management system called "Water Users' Associations" (WUAs). These associations are organized by individual farmers for operating, maintaining, and rehabilitating the irrigation and drainage infrastructure. However, the concept of the WUAs is quite new in these countries, and the governments need donors' support and assistance for establishing and developing WUAs, as well as in training WUA staff and members.

Figure 2. Deteriorated Irrigation Canal (Thurman, 2001)

The Asian Development Bank (ADB), the World Bank, and other donors have, therefore, funded projects that include not only the rehabilitation of deteriorated irrigation and drainage infrastructure but also the establishment and development of WUAs (Table 1). After the completion of the donors' projects, WUAs are expected to play an important role in the operation and maintenance (O&M) of the irrigation and drainage infrastructure. Thus, WUAs are expected to also play a large role in maintaining a sustainable irrigation and drainage infrastructure.

Table 1. Main Irrigation Projects for WUA Development in Central Asia

Country	Project	Donor
Kyrgyz Republic	Agriculture Sector Program	ADB
	Agriculture Area Development Project	ADB
	Irrigation and Rehabilitation Project	WB
	On-Farm Irrigation Project	WB
	Natural Resources management Program	USAID
	Water User Associations Support Program	USAID
	Integrated water Resources Management in Fergana Valley	SDC&IWMI
Uzbekistan	Ak Altin Agricultural Development Project	ADB
	Grain Productivity Improvement Project	ADB
	Amu Zang Irrigation Rehabilitation Project	ADB
	Rural Enterprise Support Project	WB
	Drainage, Irrigation and Wetland Improvement Project	WB
	Natural Resources management Program	USAID
	Integrated water Resources Management in Fergana Valley	SDC&IWMI
Kazakhstan	Water Resources Management and Land Improvement Project	ADB
	Irrigation and Drainage Improvement Project	WB
	Natural Resources management Program	USAID
Tajikistan	Agriculture Rehabilitation Project	ADB
	Irrigation Rehabilitation Project	ADB
	Farm Privatization Project	WB
	Rural Infrastructure Rehabilitation Project	WB
	Natural Resources Management Program	USAID
	Water User Associations Support Program	USAID
	Integrated Water Resources Management in Fergana Valley	SDC&IWMI

Remarks: 1) ADB: Asian Development Bank
2) WB: World Bank
3) USAID: United States Agency for International Development
4) SDC: Swiss Development Cooperation
5) IWMI: International Water Management Institute

Organizational Structure and Roles of Water Users' Associations

The International Water Management Institute (IWMI, 2003) proposed a typical pyramidal and hierarchical organizational structure for WUAs (Fig. 3). In the proposed structure, a general assembly or a representative assembly has the right to vote on resolutions and elects the members of a revision commission, WUA council, and dispute resolution commission, each of which has different origins and proposes resolutions to the general or representative assembly.

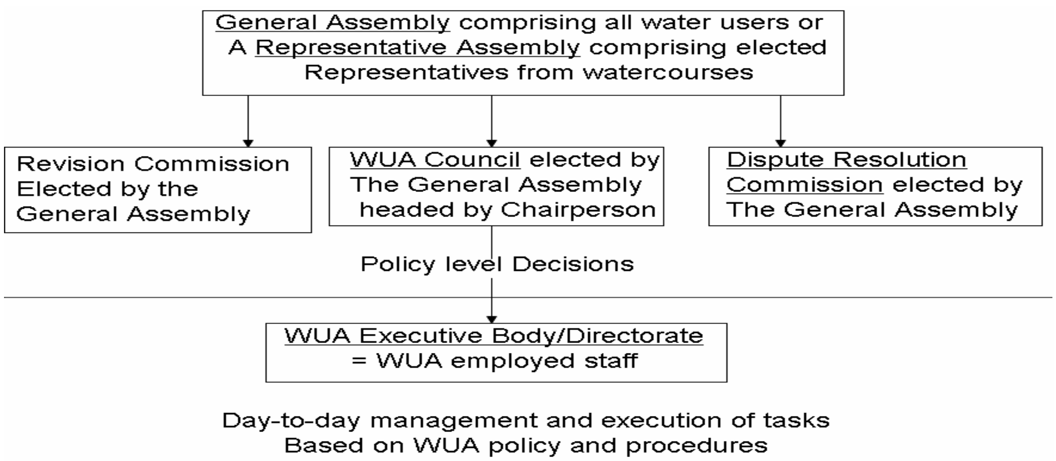


Figure 3. Typical Organizational Structure of a WUA (IWMI, 2003)

The WUAs' roles would include (1) taking responsibility for the O&M of the irrigation and drainage infrastructure, (2) collecting fees from members for O&M and for repayment, (3) ensuring equitable and timely water supply to members, (4) taking the responsibility of cost recovery, (5) participating in the projects' rehabilitation of irrigation and drainage infrastructure, and (6) training members. The ADB emphasizes the importance of the phased turnover of responsibilities for O&M and cost recovery to WUAs (ADB, 2003c).

Since gaining independence from the former Soviet Union, the Central Asian countries have used different strategies in the shift from socialist to capitalist regimes, including in the agricultural sector (Table 2). In this study, the agricultural market reforms, current status of irrigation and drainage infrastructure, and the roles of WUAs for O&M in the Kyrgyz Republic and Uzbekistan are reviewed and analyzed.

These two countries were selected because they are very different in their strategies on agricultural reform. The Kyrgyz government has adopted a rapid approach for moving from a planned to a market economy in terms of agricultural reform and development of WUAs. The Kyrgyz Republic joined the International Monetary Fund (IMF) in 1992, and it has joined the United Nations, the World Bank, the ADB, and other international organizations. The Uzbek government, on the other hand, has taken a much more gradual approach for moving from a planned to a market economy. The government is partly under the old regime and objects to liberal agricultural reforms, including in its cotton market, even though Uzbekistan is the fifth largest producer of cotton in the world.

Table 2. Outline of Central Asian Countries
(Based on Website of Central Asia and Caucasus Research Institute)

Country	Kyrgyz Republic	Uzbekisutan	Kazakhstan	Tajikistan	Turkmenistan
Area (km2)	Total: 198,500 Land: 191,300 Territorial Waters: 7,200	Total: 447,400 Land: 425,400 Territorial Waters: 22,000	Total: 2,717,300 Land: 669,800 Territorial Waters: 47,500	Total: 143,100 Land: 142,700 Territorial Waters: 400	Total: 488,100 Land: 488,100 Territorial Waters: 0km2
Boundary (km)	Total: 3,878	Total: 6,221	Total: 12,012	Total: 3,651	Total: 3,736
Climate	Continental dry climate, moderate in northern foothills, subtropical in Fergana Valley.	Temperate desert, hot summer, moderate winter.	Continental climate, cold winter, dry and hot summer, dry climate.	Continentally hot summer and moderate winter.	Subtropical and desert.
Geographical Features	The mountainous region of the Tian Shan covers over 80% of the country, with the remainder made up of valleys and basins.	Dry, double-landlocked country of which 10% consists of intensely cultivated, irrigated river valleys.	The terrain extends west to east from the Caspian Sea to the Altay Mountains and north to south from the plains of Western Siberia to the oases and deserts of Central Asia.	Mountains cover 93 percent of Tajikistan's surface area. Pamir Mountains and Alay Mountains, Tian Shan skirts northern Tajikistan.	90% of the country is covered by the Karakum Desert. The center of the country is dominated by Turan Depression.
Natural Resources	Water power, gold, rare metal, coal, natural gas.	Natural gas, petroleum, coal, gold.	Petroleum, natural gas, coal, steel.	Water power, uranium, mercury.	Petroleum, natural gas, sulfur.
Land Use (2005)	Arable Land: 6.55% Agriculture: 0.28% Others: 93.17%	Arable Land: 10.51% Agriculture: 0.76% Others: 88.73%	Arable Land: 8.28% Agriculture: 0.05% Others: 91.67%	Arable Land: 6.52% Agriculture: 0.89% Others: 92.59%	Arable Land: 4.51% Agriculture: 0.14% Others: 95.35%
Irrigated Area (km2 in 2003)	10,720	42,810	35,560	7,220	18,000
Natural Risks	Water pollution, salinization.	Drought in the Aral Sea, desertification, industrial water pollution, overusage of fertilizer and pesticide, salinization, soil contamination.	Earthquake in southern areas, debris-avalanche near Almaty	Inappropriate sanitation, increased salinization, industrial pollution, pesticide.	Soil pollution, groundwater pollution, pesticide, desertification, water pollution, deforestation, water pollution in the Aral Sea, drought in the Aral Sea.
Population (2006)	5,213,898	27,307,134	15,233,244	7,320,815	5,042,920
Remarks	Independent in 1991. Implementing the most rapid approach towards a market economy among the Central Asian countries. The most positive for rapid reform.	Independent in 1991. President Karimov amended the Constitution to extend his tenure until 7 years in 2002. Implementing gradual approach towards market economy, with a focus on political stability.	Independent in 1991. Domestic situation is stable under the strong leadership of President Nazarbaev. Maintains good relationship with the ADB, World Bank, and the EBRD. Implementing market orientation and development.	Independent in 1991. Suffered from civil war. Provisional cease-fire agreement was signed in 1994. Peace agreement was signed in 1996. Final agreement was signed in 1997. General election was carried out in 2000.	Diplomatic policy is "positive neutrality." Acknowledged as a permanently neutral country by the United Nations in 1995. Original policy in Central Asia.

KYRGYZ REPUBLIC

Agricultural Reform

The rapid change of the political and economic systems due to the independence in 1991 had done a great deal of damage to all farm products. In 1993 and 1994, agricultural production decreased more than 30 percent due to shortages of agricultural inputs, a decrease in international trade, and a lack of agricultural credit. Farm income also rapidly declined as compared with other sectors' income. Farm income fell from 90 percent of other sectors' income in 1990 to 45 percent in 1994.

Three important issues in the agriculture sector are: (1) severe land degradation, (2) inefficient utilization and management of water resources, and (3) overuse of forest resources. These issues are mainly caused by policies that favor economic development over the sustainable use of natural resources.

Among the Central Asian governments, the Kyrgyz government has most rapidly adopted reform policies for the agricultural sector. These reforms focus on (1) developing and promoting market institutions, (2) encouraging competitive forces in the newly established market, (3) preserving environmental resources, and (4) reorienting and strengthening the public sector. With the support of the World Bank, the government also actively promoted land reform and farm restructuring by 1995.

Furthermore, the government promoted removing official restrictions from the markets and encouraged independent trade. The government abolished quota, licensing, and pricing systems to liberalize international trade of agricultural input goods and production. However, there has not been sufficient time for the reforms to take effect.

Irrigation Infrastructure

Approximately 80 percent of arable land in the Kyrgyz Republic is irrigated. Since 1995 the donors' projects rehabilitating deteriorated irrigation infrastructure have been implemented. However, Kyrgyz economic capacity is small, domestic funds are limited, and the government has difficulty increasing its international debt. Under such serious financial constraints, it is important for the government and the donors to carefully create priorities for the rehabilitation of deteriorated irrigation infrastructure.

Establishment and Development of WUAs

One of the important issues for appropriate O&M of the irrigation and drainage infrastructure in the Kyrgyz Republic is who should be responsible for O&M. The Kyrgyz government promoted the transfer of ownership of the irrigation and drainage infrastructure from the collective farms to individual water users in 1994. The government also promoted the establishment of WUAs that would be responsible for O&M of on-farm irrigation and drainage infrastructure in 1995.

The ADB provided a technical assistance (TA) of "Building Capacity for the Formation and Management of Water Users Associations", together with the Agricultural Sector Program (ASP), in 1995. The TA's objective was to strengthen the capacity of the Ministry of Water Resources (MWR) to facilitate the formation and sound management of WUAs. The TA's scope included (1) reviewing the legislation for WUAs; (2) providing advice on the procedures for organizing WUAs, irrigation fee collection, and farm level system management; and (3) training key staff at the MWR and selected regional levels (ADB, 1995).

In 2002, the Kyrgyz Republic became the first country in Central Asia to enact a comprehensive WUA law on the basis of advice provided by the ADB through the ASP. The WUA law regulates the associations' responsibilities and obligations for collecting irrigation service fees, preparing budgets, making decisions regarding O&M, appropriately distributing water, and rehabilitating irrigation and drainage infrastructure (Table 3).

Table 3. Outline of Kyrgyz WUA Law

Main Components	(1) Purpose and tasks of WUA
	(2) Activity of WUA
	(3) WUA Establishment procedure
	(4) State registration of WUA
	(5) Foundation documents of WUA
	(6) WUA membership
	(7) Rights and duties of WUA
	(8) Reception of new members into WUA
	(9) Termination of WUA membership
	(10) management organs and their powers
	(11) WUA finances and property of WUA

In addition, since 1995, the ADB, the World Bank, and other donors have funded projects for the rehabilitation of irrigation and drainage infrastructure and for establishing and training WUAs for O&M. The ADB's Agriculture Area Development Project (AADP) (ADB, 1999) and the World Bank's On-Farm Irrigation Project (OFIP) (World Bank, 2000) are examples of effective projects for the establishment and development of WUAs (Table 4).

These irrigation projects require that WUAs in the project areas pass a series of determined milestones (Fig. 4) for designing and implementing the rehabilitation of irrigation and drainage infrastructure in order to ensure that the WUAs are operating effectively (Johnson et al., 2002). When a WUA achieves the fourth milestone, it becomes a candidate for the rehabilitation of irrigation and drainage infrastructure under the projects. When a WUA achieves the seventh milestone, a rehabilitation contract can be signed with a contractor. When WUAs cannot achieve the necessary milestones, their rehabilitation projects will be postponed or they will be excluded from the project areas. These milestones enable WUAs to be sustainable bodies and to be actively involved in designing and implementing the irrigation projects.

Table 4. Outline of the Two Irrigation Projects in the Kyrgyz Republic

Project	Agriculture Area Development Project (AADP)	On-Farm Irrigation Project (OFIP)
Donor	Asian Development Bank	World Bank
Targeted Region	Chui Oblast	All 7 Oblasts
Targeted Area	55,000ha	160,000ha
Total Cost	US$ 45 million	US$ 29 million
Main Components	(1) Farm Development	(1) WUA Strengthening Services
	(2)Drainage and Irrigation (Including WUA Development)	(2) Infrastructure Rehabilitation and O&M
	(3) Development of Private Sector Marketing and Input Supply Services	(3) Implementation Support
	(4) Project Management	

Milestone 1	WUA establishment, including legal legislation and bank account opened
↓	
Milestone 2	Recruitment of WUA staff and necessary training
↓	
Milestone 3	WUA Board has prepared a plan of O&M and the general assembly has approved this plan, including setting a sustainable fee to cover O&M and irrigation service fee (ISF) costs
↓	
Milestone 4	WUA members have paid O&M costs and ISF payment to water supplier
↓	
Milestone 5	WUA and MWR have developed alternative for rehabilitation and determined their costs, involving WUA members in these discussion
↓	
Milestone 6	WUA members have selected an alternative for rehabilitation
↓	
Milestone 7	A majority of water users in the WUA have agreed to borrow the credit for rehabilitation and to repayment under the projects' terms and the WUA Board officially requests the credit and signs for repayment

Figure 4. Seven Milestones for WUA Development

WUA Issues

Rehabilitation of the deteriorated irrigation and drainage infrastructure is only one element of achieving sustainable irrigation and drainage. It is also necessary to establish sustainable WUAs that can take on O&M responsibilities. Irrigation projects of the ADB, the World Bank, and other donors employ international and domestic consultants during the project implementation period to establish and develop WUAs. However, after the completion of the projects, WUAs will have to take on O&M responsibilities by themselves and maintain financial sustainability without support. Otherwise, the rehabilitated infrastructure will yet again be allowed to deteriorate.

One of the most serious issues for sustainable irrigation and drainage in the Kyrgyz Republic is the financial weakness of WUAs. Cost recovery and the setting and collecting of Irrigation Service Fees (ISF) are critically important for sustainable WUAs.

The cost recovery under the AADP and OFIP requires farmers to repay 25 percent of the rehabilitation costs of irrigation and drainage infrastructure. However, this figure is determined politically, rather than on the basis of economic and financial analysis. Therefore, it is difficult to say whether it fully takes into account the farmers' repayment availability. Farmers may not necessarily fully understand or agree with the proposed repayment scheme when they sign repayment agreements.

The Kyrgyz government determined the ISF to be 0.03 som (US$0.0007) per ton in 1995. However, that ISF would cover only 30 percent of the total O&M costs even if 100 percent of the ISF were collected. The actual collection rate is only 80 percent, and most of it is in kind. The cash collection rate is only 30 percent (ADB, 2004).

UZBEKISTAN

Agricultural Reform

The Uzbek government has taken a more gradual approach toward agricultural reform since its independence in 1991. The government maintains production targets and procurement prices for cotton and wheat, the two main agricultural products in Uzbekistan. The slow pace of agricultural reform, particularly for cotton, reflects the government's deep concern about the potential impacts of liberalization on the country's political and social stability because cotton has the largest share of export earnings, state budget revenues, and farmers' income. This concern has been reinforced by the negative impact of rapid reform in some of the other Central Asian countries (e.g., the Kyrgyz Republic).

The pace of reform for cotton has been particularly slow. Farmers continue to suffer from excessive state intervention, including production targets that control the entire production of farms and a fixed procurement price that is below production costs. The ADB and the World Bank have requested that the Uzbek government implement more rapid reform, particularly in regard to state-controlled production targets and procurement prices for cotton and wheat.

The Uzbek government is required to implement specific agricultural reforms concerning cotton and wheat under the ADB's Ak Altin Agricultural Development Project (AAADP) (ADB, 2001) and the World Bank's Rural Enterprise Support Project (World Bank, 2001) (Tables 5 and 6). Although these specific assurances are prerequisites for implementing the irrigation projects, these reforms have not yet been fully achieved.

Table 5. Outlines of the Two Irrigation Projects in Uzbekistan

Project	Ak Altin Agricultural Development Project (AAADP)	Rural Enterprise Support Project (RESP)
Donor	Asian Development Bank	World Bank
Targeted Region	Ak Altin Region	5 Oblasts
Targeted Area	37,000ha	162,400ha
Total Cost	US$ 72 million	US$ 43.45 million
Main Components	(1) Institutional Support, Monitoring, and Evaluation (Including Organizing and Training WUAs)	(1) Rural Business Advisory Services
	(2) Rehabilitation of Irrigation and Drainage Systems	(2) Rehabilitation of Irrigation and Drainage Systems (Including WUA Development)
	(3) Farm Machinery Services	(3) Rural Finance
	(4) Project Management	(4) Credits for Agro-Service Enterprises
		(5) Project Implementation Support

Table 6. Agricultural Reform Required by the ADB and World Bank

	Required Agriculture Reform
1	The government will not increase the procurement quotas for raw cotton and wheat in the project area.
2	The government will ensure that farmers in the project area receive advance payments for cotton and wheat production on time, and the final payments within three months after crop delivery.
3	The government will review annually the state procurement prices for raw cotton and wheat, and ensure that any future adjustments of prices for each quality grade will fully reflect the annual inflation rates and changes in international border prices of input and outputs, and adjust for changes in the exchange rate.
4	The government will ensure that the farms and individuals farmers are entitled to sell their above-quota cotton and wheat to buyers in the domestic market at mutually agreed upon prices.
5	The government will review periodically its countrywide state procurement policies for raw cotton and wheat to foster and develop market competition and participation of the private sector.

Irrigation Infrastructure

Irrigation is vital to agriculture in Uzbekistan due to its arid climate. The expansion of the area irrigated began in the 1950s when a huge amount of irrigation infrastructure was constructed to supply water to semi-desert areas. Since the late 1980s, funds for O&M have been lacking. After 1991, the government budget for O&M rapidly decreased, further accelerating the deterioration of the irrigation and drainage infrastructure. Irrigation water is pumped up in many areas in Uzbekistan, and the electricity consumed pumping irrigation water is 20 percent of the country's total electricity consumption. Approximately 70 percent of the government's irrigation budget is used to pay for electricity for pumping, and the budget for O&M is underfunded. This continued lack of funding has lead to even worse deterioration in the irrigation and drainage infrastructure. It is estimated that only 55 to 66 percent of irrigated areas was appropriately operated and maintained from 2000 to 2003 (ADB, 2003a).

Establishment and Development of WUAs

The government has promoted a decentralized administration of water resources in order to cope with the budget shortage for irrigation and drainage infrastructure. Basin irrigation system authorities have been established to rationalize water allocation in every catchment area of main rivers. In addition, each basin irrigation system authority is setting up WUAs to which the responsibility for on-farm O&M is being transferred. However, WUAs do not have adequate human resources or knowledge to deliver the necessary services. Therefore, the ADB, the World Bank, and other donors are implementing irrigation projects, as well as helping to establish, develop, and train WUAs.

WUA Issues

There is no comprehensive WUA law that regulates WUAs' roles, responsibilities, obligations, and legal status in Uzbekistan. Although consultants employed by the ADB, together with the AAADP, prepared a draft WUA law, the government made no comments on it and has thus far seemed to be very reluctant to establish a comprehensive WUA law.

Farmers are required to repay some part of the total costs of repairing the irrigation and drainage infrastructure under the ADB's and the World Bank's irrigation projects. However, the cost recovery rates vary among the irrigation projects because they are determined for political and not economic reasons. The cost recovery rates are even different among irrigation projects funded by the ADB. The rates of cost recovery under the AAADP, Land Improvement Project (ADB, 2006) and Grain Productivity Project (ADB, 2003b) are 39 percent, 29 percent and 65 percent, respectively.

The government's O&M budget expenditure in 2002 was about US$130 million. According to estimates of the Ministry of Agriculture and Water Resources, however, the annual requirement for O&M and depreciation is US$550 million. These estimates do not fully consider energy prices, which could add another US$200 million per year to the cost.

Under the AAADP, WUAs are required to be responsible for the O&M of on-farm irrigation and drainage infrastructure after the completion of a project. The state will continue O&M of inter-farm irrigation and drainage infrastructure for a limited period. However, when WUAs have adequate human resources and knowledge for appropriate O&M, WUAs will be also responsible for the O&M of inter-farm irrigation and drainage infrastructure.

DISCUSSION

Comparison of WUAs in Japan and in the Kyrgyz Republic and Uzbekistan

In Japan, WUAs were originally established more than 200 years ago, while they have only recently begun to be established in the Kyrgyz Republic and Uzbekistan. Japan's WUAs represent a typical example of the successful establishment and development of WUAs. In addition, WUAs have been successfully established in some developing countries with the support of the ADB, the World Bank, and other donors.

WUAs in Japan

In general, WUAs in Japan are well organized, their financial status is balanced, and their staffs are well trained. They were established more than 200 years ago in the Edo era and have historically developed in traditional rural areas. The current WUA law was established in 1949. Currently, the members of WUAs are the actual farmers instead of land owners, and they have comprehensive responsibilities, ranging from the implementation of civil works for irrigation and drainage infrastructure to the O&M (Kunihiro, 1988). The staff and members have enough expertise for O&M, and members can afford to pay for cost recovery and ISF.

Approximately two-thirds of the vast irrigation and drainage infrastructure in Japan, including dams, headworks, and irrigation and drainage canals, is operated and maintained by WUAs. ISF collection from farmers covers the O&M costs for the irrigation and drainage infrastructure. The total O&M cost in 2000 was 225,700,000 yen (US$1,900,000), and WUAs paid for approximately two-thirds of the total O&M costs. Healthy financial management of WUAs is essential for appropriate O&M.

WUAs in the Kyrgyz Republic and in Uzbekistan

The concept of WUAs has only recently been introduced, with the support of the ADB, the World Bank, and other donors, in the Kyrgyz Republic and in Uzbekistan mainly because of the governments' lack of funds for O&M. The WUAs in these countries are therefore not historically established. In the Kyrgyz Republic, the comprehensive WUA law has been established, but appropriate implementation remains an issue. In Uzbekistan, a comprehensive WUA law has not been established, which is a prerequisite for the appropriate management of WUAs.

CONCLUSIONS

In this paper, the elements of agricultural reform, the current status of irrigation and drainage, and the roles of WUAs in the O&M of the irrigation and drainage infrastructure in the Kyrgyz Republic and Uzbekistan are reviewed and analyzed. These countries have begun to use WUAs to provide for efficient and sustainable O&M of the irrigation and drainage infrastructure. The ADB, the World Bank, and other donors have implemented irrigation projects not only for rehabilitating deteriorated irrigation and drainage infrastructure, but also for establishing and developing WUAs. However, WUAs in Central Asia are still weak. The following steps must be taken to ensure that WUAs are able to take on the required responsibilities for sustainable irrigation and drainage in Central Asia: (1) establishment and appropriate implementation of comprehensive WUA laws; (2) healthy financial management, including cost recovery and ISF; and (3) provision of appropriate training of WUA staff and members.

Financial sustainability after the completion of the donors' irrigation projects is crucial. Healthy financial management of WUAs requires determining the appropriate rate of the cost recovery for the rehabilitation of the irrigation and drainage infrastructure and setting an appropriate ISF. These decisions should not be made on a political basis but rather on the basis of economic and financial analysis, taking into account farmers' ability to pay. Collection rates of the cost recovery and ISF should also be improved. These issues should be addressed, taking into account lessons learned from the successful experiences of WUAs in Japan, as well as in some developing countries.

REFERENCES

[ADB] Asian Development Bank (1995): Report and Recommendation of the President to the Board of Directors on a Proposed Loan and Technical Assistance to the Kyrgyz Republic for the Agriculture Sector Program.

Asian Development Bank (1999): Report and Recommendation of the President to the Board of Directors on a Proposed Loan and Technical Assistance Grant to the Kyrgyz Republic for the Agriculture Area Development Project.

Asian Development Bank (2001): Report and Recommendation of the President to the Board of Directors on a Proposed Loan and Technical Assistance Grant to the Republic of Uzbekistan for the Ak Altin Agricultural Development Project.

Asian Development Bank (2003a): Report and Recommendation of the President to the Board of Directors on a Proposed Loan and Technical Assistance Grant to the Republic of Uzbekistan for the Amu Zang Irrigation Rehabilitation Project.

Asian Development Bank (2003b): Report and Recommendation of the President to the Board of Directors on a Proposed Loan and Technical Assistance Grant to the Republic of Uzbekistan for the Grain Productivity Improvement Project.

Asian Development Bank (2003c): Water for All; The Water Policy of the Asian Development Bank.

Asian Development Bank (2004): Technical Assistance to the Kyrgyz Republic for the Study on Pricing Systems and Cost-Recovery Mechanism for Irrigation.

Asian Development Bank (2006): Report and Recommendation of the President to the Board of Directors, Proposed Loans and Technical Assistance Grant Republic of Uzbekistan: Land Improvement Project.

Central Asia and Caucasus Research Institute: http://cari.727.net/.

[IWMI] International Water Management Institute (2003): How to establish a Water Users Association?

Johnson III Sam H, Stoutjesdijk J, and Djailobayev N (2002): Irrigation Reform in the Kyrgyz Republic, Sixth International Seminar on Participatory Irrigation Management, Institutional Options for User Participation.

Kunihoro Y (1988): Theory and Implementation of Irrigation Infrastructure Management, Chikyusha Press (Japanese).

Thurman M. (2001): Irrigation and Poverty in Central Asia: A Field Assessment.

World Bank (2000): Project Appraisal Document on a Proposed Credit in the Amount of SDR 14.9 Million (US$20 Million Equivalent) to the Kyrgyz Republic for an On-Farm Irrigation Project.

World Bank (2001): Project Appraisal Document on a Proposed Loan in the Amount of US$36.14 Million to the republic of Uzbekistan for a Rural Enterprise Support Project.

World Bank (2003): Irrigation in Central Asia – Social, Economic and Environmental Considerations.

CHARTERED WATER USER ASSOCIATIONS OF AFGHANISTAN SELF-FINANCING, SELF-MANAGING, SELF-GOVERNING

John E. Priest, PE[1]
Eng. A. Tawab Assifi, PE[2]
Eng. M. Ibrahim Sultani[3]

ABSTRACT

Ninety percent of the irrigators of Afghanistan own, operate and maintain canal systems. Traditionally, “Mirabs” manage water deliveries. They are chosen by water users, collect revenues and administer a limited O&M budget.

The canal systems were in poor condition and delivered adequate water to approximately 1/3 of irrigated areas in 2003. Yet, international agencies, UN and IBRD, reported that agriculture provided 75 to 90 percent of GDP and employment. The 3-year “Rebuilding of Agricultural Markets Program” (RAMP) was designed by USAID and awarded to Chemonics International, July 2003. RAMP Infrastructure undertook the rebuilding of irrigation systems. Since government lacked financial resources, a program to incorporate Mirabs into a Self-Governing Water User Association (WUA), based on legal chartering, was designed by Chemonics International and executed by Development Alternatives Inc (DAI). Undertakings, to form a WUA for the 14,500-hectare Injil Canal Command of Herat Province, were:

- Scoping and funding to achieve chartering of a WUA.
- Convince an Afghan of stature to lead the program (Eng. Tawab Assifi).
- Form capable Afghan Organizational Team (included noted jurist - Islamic and Civil law).
- Review and possibly modify laws and regulations (chartering of WUAs was written into a New Water Law).
- Map system and set up accurate voter (water user) registers.
- Conduct elections for a General Assembly of water users.
- Rebuild structures, Hari Rud/River (Head Works with silt ejector) to water intakes (200 each).

Elections were held early during 2006, key personnel were trained, and equipment was transferred to the Injil WUA at mid year by RAMP/Chemonics.

INTRODUCTION

USAID awarded a contract for $150 million to Chemonics International for the Rebuilding of Agricultural Markets Project (RAMP) July 2003. The infrastructure component of the project resulted, by June of 2006, in the construction of 600 kilometers of roads, 150 market processing

[1] Consultant, 2442 West Dry Creek Court, Littleton CO 80120, Priestjohn@aol.com
2 Consultant, 12493Whitworth Place, Tustin CA 92782, tawabassifi@yahoo.com
3 Director of Infrastructure, ASAP, Chemonics International, Ministry of Agriculture, Kabul Afghanistan, mibrahimk1344@yahoo.com

buildings, 10 cross river weirs and gated river intakes, and the rehabilitation of canals and canal structures serving 500,000 hectares of irrigated lands. It soon became clear that the government was neither organized nor did it have the financial capacity to manage, maintain and operate the rebuilt irrigation systems. A special program to establish self-financing, self-managing water user groups was formulated by Chemonics and awarded to DAI for execution. Our two companies working together, succeeded in establishing a functioning Water Users Association (WUA) for the 14,700-hectare Injil Canal Command that lies along the Hari Rud (River) in the vicinity of the City of Herat in the west of the country, Figure 1. This was accomplished in a short period of 18 months due to our taking advantage of circumstances that prevailed in Afghanistan. Four factors of importance were: 1) persons of stature were available and dedicated to the task, 2) the Afghan traditions of owner operation of irrigation systems, 3) the ancient Mirab (Water Master) system of imperfect water control and financing, and 4) the coincidence that a new water law was being formulated.

Importance of Self Sustaining Agriculture to the Afghan Economy

Agricultural production along with related enterprises is variously reported to generate 75 percent to 90 percent of the GNP, employment and commerce of Afghanistan. Irrigated agriculture and livestock production is the mainstay of agriculture. The program to develop replicable WUAs was directed specifically toward changing the agricultural sector from one that anticipates financial transfers from the Central Government to one that becomes self-sustaining and ultimately returns revenues to the provincial and central governments.

It also is envisioned that WUAs and Federations of WUAs will maintain an entire canal and drainage system from farm gate to the river. At that point they will interface with River Basin Commissions that now are being formed.

Program for Reconstruction

From the time of the Soviet invasion in the late 1970s until the expulsion of the Taliban in 2002, river diversions and irrigation systems deteriorated due to lack of financing and turmoil. In coordination with the Minister of Irrigation an approach based on priorities was adopted by RAMP/Chemonics. River diversions would be rebuilt to maximize timely water diversions and canal cleaning, and structures rehabilitation would be undertaken using hand methods where possible to transfer money immediately to villagers. The cleaning of canals and rebuilding of water dividers, control structures and turnouts was intended to reestablish flows to water users along the middle and lower reaches of canals that had been out of operation sometimes for as much as 15 years.

Some fifty contracts were awarded by RAMP/Chemonics for construction of infrastructure – river structures, canals, drains, roads, and buildings. As the contracts were completed and handed over to representatives of concerned ministries, provincial authorities and citizens groups, commitments were made to carry out management, operation and maintenance. However, it became apparent that resources and organization for sustaining the irrigation systems were inadequate to the task.

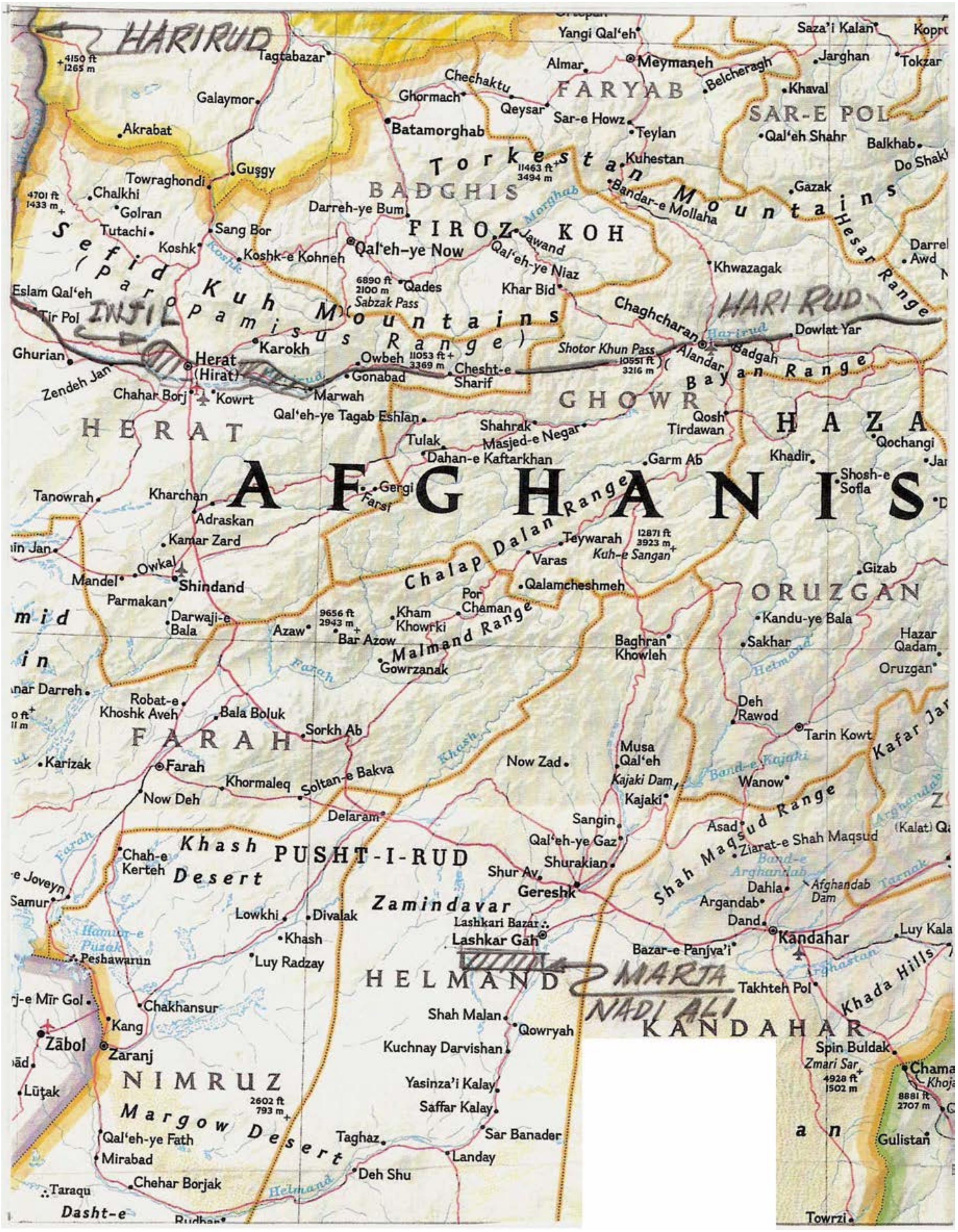


Figure 1. Newly Established Water User Associations of Afghanistan
The Injil Canal Area of Herat Province and Marja and Nadi Ali Areas of Helmand Province

The Importance to Restructuring of System Ownership, Management and Operation

Several conditions unique to Afghanistan in the ownership, management, operation, and maintenance of irrigated lands and irrigation systems presented opportunity to proceed rapidly to institutional restructuring.

Some 90 to 95 percent of irrigated land is privately owned, and for centuries irrigators have constructed and operated canal systems to provide water to the seasonally parched agricultural lands. Government intervention for the development of irrigation has been minimal with the exception of two major developments.

One development is serviced from the Helmand/Arghandab Rivers, in the south of the country. The total area served is in excess of 150,000 hectares. The major dams and storage reservoirs with a large hydro power plant, canals, and drains were built a half century ago by the US Government on the model of TVA. Current operations are being continued by the under-funded and disorganized Helmand Area Valley Authority (HAVA). The second government development is that for the 50,000-hectare Nangarhar Valley (NVDA) project built by the Soviets. The system lies along the right bank of the Kabul River and receives its water supply from the Kabul River which is headed up at a reservoir near the City of Jalalabad.

Even in Helmand, Kandahar and Nangarhar land is privately owned. It is the canal and drainage systems that remain under government control. Thus there is not strong resistance in government circles to the landowners managing their affairs. It is recalled that during a visit to the Governor before program initiation in Herat, he noted that the development of WUAs would simplify his burdens. No longer would he be faced with gunshot resolutions of disputes because there would be a controlled well established dispute resolution process, to be exercised by the landowners themselves.

There exists an ancient and imperfect system of water control and revenue collection through Mirabs. The Mirab system is practiced throughout the Central Asian countries that formerly were part of the Persian Empire. Mirabs are water masters who are elected by the water users to supervise water distribution, provide system maintenance and to resolve disputes among water users. Mirabs are individuals and there are several in the Injil Canal Command. They are influenced by a Mirab Bashi who is the senior Mirab and often has a dual political role of Wakil or sub-Governor of a District of a Province. Mirabs do not have the legal, organizational, or institutional capacity to efficiently respond to the needs of water users, to effect changes, and to maintain and operate a system. In practice, Mirabs are often dominated by power structures (local and government) to the detriment of water users.

As in many parts of the world, irrigation waters are over appropriated to the upper laterals of a canal command, with some water reaching the middle reaches of the system and little to no water reaching the tail portions. This condition has been exacerbated in Afghanistan due to turmoil-generated neglect over the past 25 years and due to the emergence of armed power brokers who have illegally appropriated water. Because lower canal water users have been deprived of adequate water and because maintenance has been difficult to achieve, the lower reaches of canal have silted and fallen into disrepair to the point that lands have gone out of production or have reverted to rain fed agriculture. The tradition of Mirabs provided a firm basis in society for the acceptance of and the need for a Chartered WUA with strong organizational capacity based firmly on legal authority.

Mirabs collect from each producer a percentage of crop value. Funds are disbursed at the discretion of the Mirab and are inadequate to the maintenance and rehabilitation needs. The important aspect of this element of the Mirab system is that there is a tradition of user pays and Afghanistan is not saddled with the certainty that God provides the water and therefore it is entirely free.

With the recognition of both the need for WUAs and the unique potentials that exist in Afghanistan, the elements necessary to successful implementation were presented to USAID and were budgeted and approved.

Elements Key to Successful Development of WUAs

The program was formulated in the context of the situation that prevailed in 2004.

The first and primary task was to enlist the right person to lead the effort. He was Eng. A. Tawab Assifi. His distinguished career and great strength of character justify his legendary status and access to government circles including the President of Afghanistan and the Ambassador of the United States and conversely with water users across the country, particularly in Helmand and Herat Province. Tawab was Chief Engineer of HAVA during the 1970s, he was Governor of Herat Province for three years, and then was Minister of Mines and Energy. From that post he was imprisoned by the Communists for three years in the infamous Pul-i-Charki. He was imprisoned with some ten other ministers most of whom perished. Tawab made his way to California where he was involved for 20 years with Water Districts. He had returned to Afghanistan as COP of the DAI AREA program for rebuilding of irrigation works and was well situated to take charge of a water user program. The program was designed to: 1) review laws and regulations with a view to making amendments and/or drafting new legislation, 2) accessing ministers to be sure the cabinet would approve enabling legislation for the chartering of water users, and 3) develop a model charter and bylaws that would be acceptable to the water users themselves. Once there was a model, Tawab had to sit with the Shuras (councils of local elders) and religious leaders to gain acceptance and participation.

Tawab recruited a talented, dedicated team, Dr. Basir Ahmed, Deputy Team leader, Dr. Abdul Hakim, a jurist knowledgeable of both Civil and Shura law, and a team of engineers, economists, and sociologists who conducted technical, census, and organizational work along with training of trainers and conduct of workshops.

Both Dr. Basir and Dr. Hakim are experienced and affable persons who work well with government officials, members of the donor community, the local Shuras (councils of elders and natural leaders) and individual water users.

As noted above, *the program was carefully formulated and received USAID approval for sub-contracting to DAI with an adequate budget*. The program was initiated in November 2004 in two Districts of the Middle Helmand Irrigation system, Nad-i-Ali (14,000 hectares) and Marja (15,000 hectares). Ten months into the program, chartering models and bylaws had been formulated, a model had been selected by the water users, and two General Assemblies had been formed based on elected representatives from the communities of sub-laterals. Efforts to form a Management Board were suspended due to deteriorating conditions of security that developed in Helmand Province.

Concurrently with the election of General Assemblies at the field level, the review of laws and regulations proceeded to the point that the National Water Law was being modified to legalize chartering of WUAs from the abstract to the specific. Thus, *the twin approach of working from the top down and from the bottom up resulted in success at both levels in a relatively short time*.

However, with the deteriorating security situation, the program was transferred to the Injil Canal system in Herat province where a program of construction and reconstruction was well under way. The DAI contract was extended through April 2006 and the budget was increased to somewhat more than $1.3 million.

MODEL DEVELOPMENT

It was deemed essential that two or more models be conceptualized and presented to water users to facilitate adoption with adaptations that would fit local circumstances. Existing laws, regulations and customs were reviewed, analyzed, and discussed at workshops to facilitate development of model constructs and bylaws that would be easily applied with the force of law. Input to model development included information from WUA Congresses that are held annually in Turkey and from a visit to India where several forms of WUAs are in use, some successful and some not. There are in the ministries of Kabul, advisors from the EU, IBRD, USAID, the ADB, the UN, JICA, and other donors. As well, the Department Heads and Deputy Ministers are knowledgeable of the potentials for organizations that can manage canal systems. Knowledge resident with each of these groups, as recorded at a series of workshops, was factored into the process of charter development.

Laws, Regulations, and Customs

The existing body of law (2004) authorized the formation of associations and other provisions of the law would have permitted management of a large group. However, provisions of the law were not specific to WUAs. Fortuitously, the National Water Law was being redrafted. Engineer Tawab Assifi engaged the key members of his team on the committee of the Ministry of Energy and Water Resources that was preparing the new draft. The result is an article that specifically authorizes the chartering of WUAs with powers to manage, finance and operate and maintain canal systems. Drafting of the water law had been completed by mid-2006 and a majority of ministers had been briefed and agreed to the new law in a cabinet session. Yet to be defined is which ministry will authorize and be a repository of charters; our initial preference was the Ministry of Justice, essentially a neutral party to water distribution and use.

Provisions of Models

Models are comprised of Charters and Bylaws, entitled “Internal Regulations of Water Users’ Association”. The provisions of the two documents were developed taking into account the results of extensive surveys among water users that tested and determined attitudes toward payment of dues, work-in-kind, use of labor and machinery, misappropriation of water, and the appropriate role of government.

Key provisions of the adopted charter determine the structure of a WUA with regard to formation and governance. The Bylaws are directed toward important issues of management including Article 14 of the Injil documents entitled “Method of Dispute Resolution”. A hierarchy of appeal and arbitration is established for the settlement of disputes regarding water delivery and turns, non-payment of dues, and failure to participate in collective efforts of cleaning and maintenance.

ESTABLISHMENT OF A WUA, INJIL CANAL, HERAT PROVINCE

Two activities were carried out in parallel for establishment of a WUA for the Injil Canal, a physical survey and introduction of the parameters associated with establishment of governing institutions.

Physical Survey and Mapping

Surveys using GPS units were made to locate the courses of the main and branch canals of the Injil command. Laterals and sub-laterals were stationed and numbered and identified on existing maps of the area. Separate maps were prepared for three reaches of the canal, the upper (bala bulok), middle (meeyan bulok) and lower (payeen bulok). Water users are organized according to these three divisions of the canal command. Figure 2 is for Bala Bulok and it shows the system from the area of the intake on the Hari Rud to Lateral number 30. Table 1 is a tabulation of coordinates and station locations for the first 27 of the 99 laterals and sub-laterals of the system. Additionally the table presents data for the number of farm families and the number of jeribs ($1/6^{th}$ of a hectare) served by each sub-lateral. The census was completed following principles of a Participatory Rural Assessment (PRA) with Mirabs and water users participating.

Basics of Institutional Model for Adaptation by Water Users

Irrigation systems and practices differ by region of the country. Ownership, structure and water rights practices differ by irrigation system. Therefore, for each new WUA to be established, the basic model will have to be adapted to local conditions.

Socio-economic aspects including capabilities and capacities of residents and their willingness to finance administrative costs of the association are among the primary considerations that determine the form of the WUA. The structure chosen should be that which is simple, cost effective and easy to run.

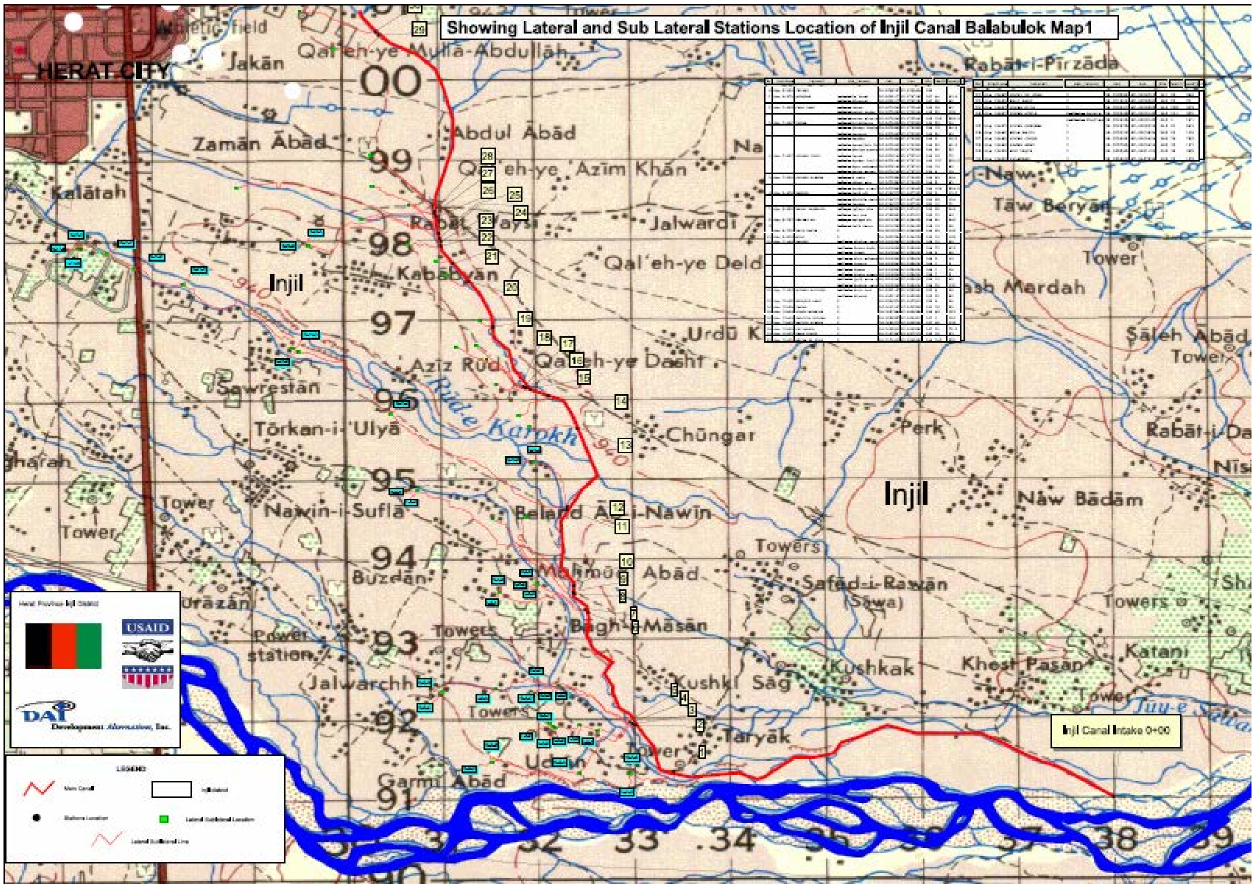


Figure 2. Head Reach (Bala Bulok) of Injil Canal

Basics of Institutional Model for Adaptation by Water Users

Irrigation systems and practices differ by region of the country. Ownership, structure and water rights practices differ by irrigation system. Therefore, for each new WUA to be established, the basic model will have to be adapted to local conditions.

Socio-economic aspects including capabilities and capacities of residents and their willingness to finance administrative costs of the association are among the primary considerations that determine the form of the WUA. The structure chosen should be that which is simple, cost effective and easy to run.

The basic model consists of an elected General Assembly and a Management Board. The General Assembly includes the elected representatives of all water users. Members are to be elected directly by the water users for a fixed term. Day to day operations of the WUA are to be run by the Management Board, which is elected from among members of the Assembly.

The Management Board is to appoint a General Manager who as Head of an Executive Board has the authority for recruitment of personnel, distribution of water, appointment of Mirabs and

O&M of irrigation systems. The Executive Board is to consist of a General Manger, a Deputy General Manager, a Hydro-technical Manager, a Treasurer, an Accountant, a Secretary and the Mirabs who are to work under the direction of the Hydro-technical Manager. The General Manager and his deputy may wear more than one hat.

The Mirabs, in their respective command areas, are to be responsible for distribution of water in accordance with an operational plan.

The budget for the association is to be prepared by the General Manager and approved by the Board and the General Assembly. The members are responsible to fix the authority and ceiling of the expenditures to be incurred by the General Manager. General Management is to prepare and present Annual budgets and programs of expenditure for approval by the Board two months before the end of a year.

The basic Charter and Regulations have been prepared to promote transparency in the receipt and disbursement of funds by the WUA. Income of a model association typically will come through contributions and commitments of land owners and water users in accordance with provisions of the Charter, By-laws and Regulations as adopted by the particular Association.

The Injil WUA

The Injil WUA consists of a General Assembly and a Management Board. The General Assembly has 55 members and the Management Board has 11 members. The members of the General Assembly are elected by the water users of the Injil Canal, and the members of the Management Board are elected by members of the General Assembly.

The Management Board is comprised of a Chairman and 10 members who have active management duties. It was elected on April 9, 2006 and immediately began a program of training.

Election of the General Assembly

Election of the Members to the General Assembly of the Association took place based on laterals and sub-laterals along the Injil Canal. The Injil canal has 99 laterals and 54 sub-laterals that provide water to the irrigators as well as to the water users in urban areas of Herat City.

There are 30 laterals and 37 sub-laterals in the upper segment of the Injil Canal. There are 37 laterals and no sub-laterals in the middle reach of the canal. In the tail reach there are 32 laterals and 17 sub-laterals. Besides irrigators of the middle canal reach, governmental units including Herat City, the City Prison, and the Education, Agriculture and Police departments are using water from the Canal. Each department administers a number of laterals.

Thirty representatives were elected from the head reach based on the 30 laterals and the 37 sub-laterals there. Twenty-four representatives were elected from the tail reach to represent water users of 32 laterals and 17 sub-laterals. Five representatives only were elected to represent water users of the 37 laterals of the middle reach of the canal.

Table 1. Laterals and Sub-Laterals of the Injil Canal from River Intake to Station 11+495

No	Stations	Lateral	Sub_latera	Lat	Lon	Elv	Famili	Landji
0	Sta 0+000	INTAKE		34.2638127	62.2930994	954		
1	Sta 6+679	ATAKHAN	L-1-A-Ala kozai	34.2622177	62.2767183	947	44	69.5
			S-1-B- Khogyani	34.2622177	62.2767183	947	26	42
2	Sta 7+655	CHAR BAGH	R-2-A- Udran	34.2670440	62.2732460	945	39	83
			R-2-B-Gonbad ponba	34.2670440	62.2732460	945	29	169
			S-2-C-Buzdan alenja	34.2670440	62.2732460	945	129	528.9
3	Sta 7+656	UDRAN	L-3-A-Childokhtar	34.2672500	62.2729990	946	23	34
			L-3-B- Chahar kocha	34.2672500	62.2729990	946	15	24.5
			L-3-C- Zeyarat	34.2672500	62.2729990	946	24	46
			L-3-D- Baghha	34.2672500	62.2729990	946	9	10.5
			L-3-E- Besmellah kh	34.2672500	62.2729990	946	20	42.5
			S-3-F- Ghulam sarwa	34.2672500	62.2729990	946	24	55
4	Sta 7+657	BUZDAN INJIL	L-4-A- Tezak	34.2674140	62.2727110	942	16	73
			S-4-B- Buzdan injil	34.2674140	62.2727110	942	137	580.5
			S-4-C- Dost muhamad	34.2674140	62.2727110	942	19	85
			R-4-D- Baghe masan	34.2674140	62.2727110	942	4	10
5	Sta 7+658	BUZDAN ALENGA	L-5-A- M Azim	34.2675380	62.2724230	944	29	904
			R-5-B- Ahmad sha	34.2675380	62.2724230	944	8	83
			S-5-C- Buzdan alenj	34.2675380	62.2724230	944	129	528.5
6	Sta 9+438	NAWEEN	L-6-A- Said ali	34.2794771	62.2677939	950	5	19.5
			R-6-B- Khalifa sahi	34.2794771	62.2677939	950	25	124
			L-6-C- Paygaw	34.2794771	62.2677939	950	11	71
7	Sta 9+500	RABAT SAGHARIA	L-7-A- Jalwar cha	34.2798856	62.2674019	949	26	246
			R-7-B- Pay Gaw	34.2798856	62.2674019	949	10	46
8	Sta 9+707	BELAND AB	L-8-A- Beland ab	34.2816982	62.2664105	948	41	240
9			S-8-B- Said Qanat	34.2816982	62.2664105	948	19	90
	Sta 9+730	SAID QASIM	0	34.2815210	62.2665602	946	29	146
10	Sta 9+815	MIRI	0	34.2823964	62.2664756	949	19	109
11	Sta 11+49	KARTAH	R-11-A- Gholam sarw	34.2918540	62.2654040	948	10	20
			L-11-B- Karte bala	34.2918540	62.2654040	948	70	415

The apparent disproportionate representation of the middle reach is due to the fact that each government department that administers a number of laterals is represented by one delegate. Thus, there were 5 representatives to the General Assembly for the entire middle canal area that is served by 37 laterals.

Based on the greater area irrigated in the upper reach compared to the tail area, one representative was elected for each of the 30 laterals. The tail reach elected only 24 representatives from 32 laterals.

The 55 member General Assembly is the highest body of the Association. It makes policy and has exclusive power over the budget and elects the Management Board.

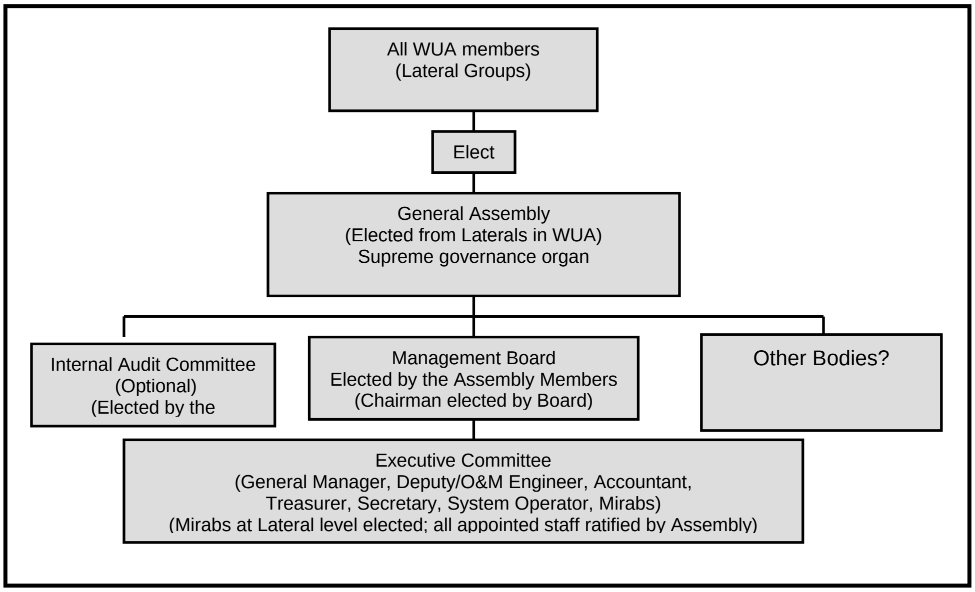


Figure 3. Bodies of the Implementing Organization

<u>Election of the Management Board</u>

Article 33 of the Charter of the Injil Canal WUA states that, “Any member of the General Assembly may nominate candidates for election as members of the Management Board and may vote at the election of members of the Board.” And Article 34 further states that, “(1) The Management Board of the Association will consist of representative members. (2) The representative members will be elected from among members of the General Assembly. Those members who secure the highest votes shall be elected as members of the Management Board.”

However, the Charter is silent on the composition and number of members of the Management Board. This is for pragmatic reasons. It is to allow flexibility in the composition of the Board to make it adaptable to different circumstances. The decision making is based on the two systems of simple and absolute majority. The activities of the WUA will be decided based on two-thirds of the total members. And decisions with respect to matters such as entering into contract and financial transactions is based on absolute majority vote, as stated in Article 39 of the Charter.

The Chairman of the Management Board is to be elected from among the Board Members. The Chairman of the Management Board also is Chairman of the Association.

The General Assembly members discussed a number of options for the composition of the Management Board. The head and tail differences became the main cause of disagreements in discussing the options. The water users from downstream, who had been deprived of water for a long period, wanted equal representation to that of the upstream members. The water users from upstream expressing disagreement to the proposal asserted that the size of their representation in the General Assembly was bigger than the downstream; therefore, they should lead the Association. The upstream has 30 and down stream 24 representatives in the General Assembly based on the number of laterals at both ends of the canal.

After lengthy discussions and disputations, the water users came to a consensus that became acceptable to all sides. The upstream agreed to equal representation, proposed by the downstream, with the condition of reserving the Chairmanship of the WUA to the upstream. And both sides nominated 5 members each to the Management Board with 1 member from the middle. Thus, an 11 member Management Board, including the Chairman, was elected.

Based on the Charter, "The members of the Management Board shall serve for a period of two years. Each elected member shall retire at the 'Annual' meeting at the end of their two year period and shall be eligible for re-election." Article 36 (2).

The Executive Body

The Management Board appointed a General Manager (GM) who heads the Executive Board. The GM is vested with the authority for management of the WUA, recruitment of personnel, appointment of Mirabs, managing distribution of water, and O&M of irrigation systems. The authorized key staff of the Executive Body includes the G M, a Deputy G M, a Treasurer, an Accountant, a Secretary, Hydro-technical Operator and the Mirabs. Staff may function in more than one of these management positions.

Training of Members of the Management Board

Following election of the Management Board and identification of key members of the Executive body, the Institution Building Team of DAI held a 3-day training workshop for them. The workshop was held from 11 to13 April 2006 in Herat City.

The objective of the workshop was to review and analyze the Charter and By-Laws in the context of the legal status and framework within which the Injil WUA was to operate. Training sessions were conducted in classroom settings. It was again designed as a participatory exercise involving extensive discussion and give-and-take regarding the Charter and the By-Laws. Trainees provided important, positive feedback regarding practices in Injil as they will affect implementation of a number of articles of the adopted Charter and By-Laws.

Training of Key Personnel of the Injil WUA in Turkey

Staff of Chemonics International sponsored and Eng. Ibrahim Sultani accompanied two key persons from the Injil Board to a two-week seminar and training session at the Annual Water Users Congress at Izmir, Turkey during May and June 2006. Hundreds of international delegates attend the Congress. The experience of traveling from villages of Herat Province to Turkey and participating in field observations of successful irrigation systems and institutions of management were invaluable for the start-up of the WUA of the Injil Canal.

Two members of the RAMP/Chemonics team had collected, two years earlier at Izmir, a large body of literature that documented a number of models, successful and failed. Reasons for success and for failure proved to be important to the development of the basic model for Afghanistan.

An Infrastructure Program in Parallel

Usually there is limited utility in the formation of a WUA if a canal system is deteriorated and not functioning to carry design flows. Therefore, once the effort in Helmand was halted due to security concerns, the Chemonics/DAI institution building team turned their attention to the 14,500-hectare Injil Canal. RAMP/Chemonics, a year earlier, had undertaken reconstruction of all structures (numbering in the 100s). An additional favorable factor was that there were, after 25 years of chaos, no illegal water diversions that could not be amicably resolved.

The Hari Rud (river) rises in north central Afghanistan near the fabled city of Bamiyan where the giant Buddas stand. The river flows west some 200 kilometers to the Province of Herat where it defines the international boundary with Iran as it flows northward into Turkmenistan in Central Asia. The river rises in high mountains some of which top out above 17,000 feet elevation. Even though snow is present nearly year round, snow melt floods are not severe in the low lands because the basin is narrow at the high elevations. Therefore, it is the early rainfall floods of February and March that often do damage. These floods occur both along the Hari Rud and emanate from Hill Torrents that cross the canals.

The Hari Rud is a braided channel approximately one kilometer wide where the intakes for the Injil Canal are located. Diversions are made through two channels, a flood flow channel and a spring channel. The spring channel is operational during summer, the low flow season. The shingle and gravel of the Hari Rud are deep and the flows of springs along the river are allocated to some 22 canals. Spring (summer) flow to the Injil Canal approximates 2.0 to 8.0 m3/s. Design flow for the main canal is 18 m3/s.

Uncontrolled flood flows from the Hari Rud and the flow of hill torrents historically have greatly exceeded canal capacity with the consequence that some parts of the system performed in the past like a creek. The most important structure of the RAMP/Chemonics program was that built at a head reach location where gravel, sand, and sediment could be returned directly to the Hari Rud.

Aqueducts that carry the canal over hill torrents, water dividers at branch canals, and lateral and sub-lateral structures were repaired and rebuilt to account for established water rights.

Now that flood flows and sediment are excluded from the canals, the water users can clean the canals in confidence that they will not be refilled with the next flood. The rebuilt structures will permit Mirabs to control flows and to realize the delivery of water in the right quantity at the required time.

Implementation of a WUA with Capacity to Control Water Delivery

The newly realized capacity of the Injil WUA to control water distribution institutionally and physically brings important benefits that did not exist with the traditional Mirab system. Important attributes of a WUA are compared with the functioning of a Mirab, Table 2.

Table 2. Outcomes - Traditional Water Management and WUAs

Current Situation	WUA
O&M: Mirabs are effective in their zone; but O&M and rehabilitation requirements exceed resource and organizational capacity	Have mandate and are organized to plan and execute work. Financing can be secured through fee collection and capital mobilization
Trust: water users place very great emphasis on trust; there is some accountability through Shuras; but Mirabs mix "use payments" for public good and their income	WUAs follow established accounting procedures and are accountable; abuses that have occurred with mixing of funds no longer are possible
Equity: there are pronounced differences in water availability in the upper, middle and lower reaches of the canal system	The WUA has procedures and personnel to manage water distribution according to rights; a process of dispute resolution is detailed in the By-Laws
Investment: use payments vary enormously among systems and are only sufficient for minimal maintenance	Establishes regular collection and use of fees and water charges; have capacity to enter into agro-business arrangements and borrowing
Government planning: Mirabs have an influential role.	Organized to ably represent interests of the people for water management

Socio-Economic Benefits of Institutionalizing Water Control Through the Injil WUA

Benefits to the community that were recognized early were a sense of ownership on the part of individual water users, that there are now in place mechanisms for resolving issues and disputes, and that illegal connections and inequitable distribution of water can be eliminated amicably.

A Sense of Ownership. A principle guiding establishment of a WUA in Herat was to meet the challenge of sustaining participation of water users in irrigation management. The Charter and by-Laws developed for the Injil WUA govern day-to-day activities of the WUA and due to the closeness of the communities each water user is effectively engaged through their representatives in the General Assembly.

The give and take that took place during the training of the members of the Management Board, made clear that the WUA was going to play an important role in resolving issues that could not be settled working through the Mirab system.

Elimination of Illegal Connections. Illegal use and stealing of water by the upstream water users is a common problem country wide. This problem results from twenty three years of war, increases in population and development of new lands that need irrigation water. Following these travails, water users were afraid of change as it often benefited only the few. Traditionally, the upstream water users had been taking considerably more than their share. In the case of the Injil Canal, some 2000 hectares near the tail of the canal remained un-irrigated for years and there were water shortages in the mid-reaches of the system.

However, water users in the Injil canal command were helped to realize that equitable distribution of water and re-establishment of water rights can be accomplished only by the water users themselves working through the legal framework of a WUA type institution.

Now that infrastructure has been rebuilt and the WUA established, the Injil Canal water users are resolving the head and tail differences amicably and have paved the way to equitable distribution of water.

TOWARD THE FUTURE

Water users are facing immense problems in irrigation water management due to destroyed irrigation infrastructure, weak organizational capability, and lack of financing. The introduction of WUAs will bring new hope for the revival of irrigated agriculture by establishing a framework for better and sustained irrigation water management and maintenance of irrigation and drainage systems. The major challenge is to inform, educate and interest international donors to finance and implement programs based on a proven model in Herat.

The Challenges of Replication

Besides the need for educating and informing donors, there is a need to engage and train a considerable body of implementers. The irrigation systems in each region of the country have their own water rights regime, physical characteristics and nature of ownership. Thus, WUA models need to be adapted to local conditions for well over 100 canal systems. Key to success will be implementation of research and surveys that are carried out with the participation of local water users before a model can be selected for each region or river basin.

Potential for Application of a Similar Model to Agriculture, Agro-industry, Extension, Transport, Storage and Marketing

USAID has in progress it's ASAP program for institutional strengthening of the Ministry of Agriculture. There should be opportunity within this program to foster alliances of WUAs and Cooperatives and/or to model Cooperatives on the chartering principle now established for WUAs.

The objective would be to put all facets of agricultural production and marketing on the basis of user pays. An additional objective would be to engage agro-industry by contracting for specified crops and using the contract as security for loans to carry out capital expenditures. Likewise storage could be developed along with transport and machinery pools. For example, transport could be used to market produce and to return from the marketplace with inputs.

CONCLUSION

The Water User Association for the Injil Canal was formed rather quickly over a period of six months. This was due to the fact that the new National Water Law had been modified to permit chartering and a model charter for WUAs had been developed. Also there was available an experienced team of institution builders that had worked in Helmand for nearly a year. Additionally, the team members were men of prestige who could interface as readily with the water user as with a minister or governor.

A contract was in place and funds were available to move forward.

Should there be interest in creating WUAs in other countries on this model, one would do well to review the entire process and observe the important elements that contributed to the success of the formation of the Injil Canal WUA.

REFERENCE

Development Alternatives, Inc. The Final Report submitted to Chemonics International, RAMP Program Office of USAID, "Water User Associations (WUAs) in Middle Helmand and Herat", Kabul, Afghanistan, pp 168; 31 May 2006

UPDATED PROCEDURES FOR CALCULATING STATE-WIDE CONSUMPTIVE USE IN IDAHO

Richard G. Allen[1]
Clarence W. Robison[2]
James L. Wright[3]

ABSTRACT

Evapotranspiration and net irrigation water requirements were determined for 123 weather station locations across the state of Idaho for available periods of record. Estimates were made for daily, monthly and annual timesteps. Updated methods were employed for calculating reference evapotranspiration (ET_r) and crop coefficients (K_c). The ET estimates cover a wide range of agricultural crops grown in Idaho and, in addition, ET estimates have been made for a number of native plant systems including wetlands, rangeland, and riparian trees. Estimates have been made for evaporation from three types of open water surfaces ranging from deep reservoirs to small farm ponds. The ET and net irrigation water requirement calculations are intended for use in design and management of irrigation systems, for water rights management and consumptive water rights transfers and for hydrologic studies. ET calculations have been made for all times during the calendar year including winter to provide design and operation information for managing land application of agriculture, food processing and other waste streams. The weather stations evaluated include 107 National Weather Service (NWS) cooperative stations measuring primarily air temperature and precipitation and 16 AgriMet agricultural weather stations. The AgriMet stations measure a full compliment of weather data affecting evapotranspiration and are located primarily in the southern part of the state. Estimates at many stations cover more than 80 to 100 year periods of air temperature data. Because only maximum and minimum air temperature are observed at the NWS cooperative stations, the solar radiation, humidity and wind speed data parameters required in the ASCE Penman-Monteith equation (ASCE-PM) were estimated similar to recommendations in ASCE-EWRI (2005) where estimates for solar radiation (R_s) were based on differences between daily maximum and minimum air temperature and estimates for daily dewpoint temperature were based on daily minimum air temperature. Estimates for wind speed were based on long-term mean monthy summaries from AgriMet stations in southern Idaho and some airport locations in central and northern Idaho. Crop evapotranspiration, abbreviated ET_c, was calculated on a daily timestep basis for improved accuracy. Daily calculation timesteps allowed for the calculation of evaporation of water from wet soil surfaces following precipitation or irrigation events. ET_c for monthly, growing season and annual periods were summed from the daily calculations. Basal crop coefficient curves were developed or organized for 42 crop and land-cover types. Scheduling of irrigations was simulated to estimate soil evaporation from irrigation wetting events using a root-zone water balance.

[1]Professor of Water Resources Engineering, University of Idaho, Kimberly, Idaho 83341. RAllen@kimberly.uidaho.edu
[2] Research Associate, University of Idaho, Kimberly, Idaho 83341
[3] USDA-ARS (ret), Kimberley, Idaho 83341

INTRODUCTION

Evapotranspiration and net irrigation water requirements have been computed for this report on a daily, monthly and annual basis for 123 weather station locations across Idaho for available periods of record. These calculations supersede calculations previously made for Idaho by Allen and Brockway (1983) and use updated methods for calculating both reference evapotranspiration (ET_r) and crop coefficients (K_c). The ET estimates represent a wide range of agricultural crops grown in Idaho and ET estimates have been made for a number of native plant systems including wetlands, rangeland, and riparian trees. Estimates have been made for three types of open water surfaces ranging from deep reservoirs to small farm ponds. ET calculations have been made for all times during the calendar year including winter to provide design and operation information for managing land application of agriculture, food processing and other waste streams. Specific details are given in Allen and Robison (2007). All data results are available via internet from www.kimberly.uidaho.edu/ETIdaho. The report can be downloaded from that site.

Crop evapotranspiration, ET_c, are needed for design and management of irrigation systems, for water rights management and consumptive water rights transfers and for hydrologic studies. Daily calculation timesteps allow for the calculation of evaporation of water from wet soil surfaces following precipitation or irrigation events. ET_c for monthly, growing season and annual periods were summed from the daily calculations.

Evapotranspiration Calculation Approach

The calculation procedure utilizes the crop coefficient – reference ET method, where a reference ET_r is multiplied by a crop coefficient. The reference ET_r represents ET from a defined, fully vegetated surface, in this case, full-cover alfalfa, and incorporates the influence of weather on the ET quantity. The K_c is defined as the ratio of actual or potential ET by a specific crop or land-cover condition to ET_r. The K_c therefore incorporates plant and cultural factors that cause ET to vary from ET_r. These factors are typically related to stage of vegetation development and wetting by irrigation or precipitation. The K_c ET_r method is widely used due to its simplicity, reproducibility, relatively good accuracy, and transportability among locations and climates. The method, when applied carefully, can produce estimates of ET that are sufficiently accurate for irrigation systems design and operation.

Reference Evapotranspiration

Reference ET has been historically calculated using a number of calculation equations and for both grass and alfalfa reference type, depending on the region of the country and local tradition. In Idaho, Allen and Brockway (1983) used the FAO-24 Blaney-Criddle equation as a reference, where the equation was calibrated to alfalfa reference ET_r using the Wright and Jensen (1972) version of the Kimberly Penman equation. The AgriMet system in southern Idaho has traditionally applied the Wright (1982) version of the Kimberly Penman, often referred to as the 1982 Kimberly Penman, which is also an alfalfa reference. Based on recent work by ASCE-EWRI (2005) on standardizing the reference ET definition and calculation for use across the United States and their recommendation to use the ASCE standardized Penman-Monteith method for standardized congruency among states and regions, we have selected the ASCE standardized Penman-Monteith for the alfalfa reference calculation. The ASCE-PM ET_r method has been shown to compare well against lysimeter measurements of alfalfa ET at Kimberly, Idaho (Wright et al., 2000) and at Bushland, Texas (Wright et al., 2000, Todd et al., 2000). Crop coefficients developed at Kimberly for the 1982 Kimberly Penman method were converted for use with the ASCE-PM-ET_r method (Allen and Wright, 2002). An alfalfa reference ET_r was utilized for consistency with historical and current practice in Idaho. In addition, the rougher aerodynamic properties of the alfalfa reference provide for more consistent values for the K_c values for a wide variety of crops and over a wide range of weather conditions (as opposed to those for grass reference bases) and the K_c values for the alfalfa reference often peak at 1.0.

The ASCE-EWRI (2005) standardized PM method for reference ET_r can be applied to either alfalfa or grass references and has the form:

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

where ET_r is the standardized reference ET for full-cover, 0.5 m tall alfalfa or for short (0.12 m tall clipped, cool season grass) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps), R_n is calculated net radiation at the crop surface (MJ m^{-2} $d^{-1}$for daily time steps or MJ m^{-2} h^{-1} for hourly time steps), G is soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps), T is mean daily or hourly air temperature at 1.5 to 2.5-m height (°C), u_2 is mean daily or hourly wind speed at 2-m height (m s^{-1}), e_s is saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature, e_a is mean actual vapor pressure at 1.5 to 2.5-m height (kPa), Δ is slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), C_n is a constant that changes with reference type and calculation time step and C_d is a constant that changes with reference type and calculation time step.

For application on a daily timestep for the alfalfa reference, C_n= 1600 K mm s^3 Mg^{-1} d^{-1} and C_d = 0.38 s m^{-1}. Units for the 0.408 coefficient are m^2 mm MJ^{-1}. The values for C_n consider the time step and aerodynamic roughness of the surface and C_d considers the time step, bulk surface resistance, and aerodynamic roughness of the surface. C_n and C_d were derived by simplifying several terms within the 'full' ASCE-PM equation of ASCE Manual 70 (Allen et al., 1989, Jensen et al., 1990) and rounding the result.

Most National Weather Service (NWS) locations report observations on a 24-hour time step basis, only. Therefore, the 24-hour calculation timestep for ET_r was applied. Daily air temperature data have been utilized in calculations to provide for better within-month sensitivity than if monthly mean data were utilized. Because only maximum and minimum air temperature are observed at the NWS cooperative stations, the solar radiation, humidity and wind speed data parameters required in the ASCE-PM equation were estimated similar to recommendations in ASCE-EWRI (2005), where estimates for solar radiation (R_s) were based on differences between daily maximum and minimum air temperature and estimates for daily dewpoint temperature were based on daily minimum air temperature. However, in this study, the Thornton and Running (1999) procedure was used for R_s rather than the Hargreaves-Samani (1982) method described by ASCE-EWRI.

a. *Daily solar radiation:*

The Thornton and Running (1999) procedure was used to estimate solar radiation where:

$$R_s = R_{so}\left[1 - 0.9\ exp\left(-B\left(T_{max} - T_{min}\right)^{1.5}\right)\right] \quad (2a)$$

$$B = 0.023 + 0.1\ exp\left(-0.2\ \Delta T_{month}\right) \quad (2b)$$

where R_s is estimated daily solar radiation, R_{so} is theoretical solar radiation on a clear day (R_{so} is computed using exoatmospheric radiation computed as a function of latitude and date and the ASCE-EWRI (2005) atmospheric transmissivity function), T_{max} is daily maximum air temperature and T_{min} is daily minimum air temperature in ^oC. Units for R_s and R_{so} are the same. Parameter ΔT_{month} in Eq. 2b represents long term average values for T_{max} and T_{min} on a monthly basis. The coefficients for Equation 2b were developed during this study using data from Thornton and Running for western locations. The use of Eq. 2a and 2b replaced the use of the Hargreaves and Samani (1982) equation that was suggested by ASCE-EWRI (2005), where $R_s = 0.16\ (T_{max}-T_{min})^{0.5}\ R_a$. Eq. 2a and 2b produce more consistent and accurate estimates of R_s on a daily and monthly basis across southern Idaho than does the Hargreaves-Samani equation, relative to measurements of R_s recorded at Idaho AgriMet weather stations. An additional advantage of Eq. 2a is that it is self limited to a maximum value R_s represented by R_{so}.

b. *Dewpoint temperature*

Dewpoint temperature, T_{dew}, was estimated from daily minimum air temperature:

$$T_{dew} = T_{min} - K_o \quad (3)$$

where T_{min} is daily minimum air temperature (^oC) and K_o is an offset that varied monthly as shown in Table 1. The K_o offsets were based on long-term records of dewpoint and T_{min} averaged from about ten AgriMet weather stations across southern Idaho and varied by month. Negative values during winter indicate that the 24-hour average T_{dew} exceeded T_{min} due to condensation of moisture during nighttime (i.e., frost, etc.) that allows T_{min} to decline with a declining nighttime T_{dew}.

Table 1. Values for dewpoint temperature offset, K_o, (^oC) to estimate T_{dew} in Idaho.

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
-2	-1.5	0	1.5	1.5	1.5	1.5	1.5	1.5	1	-1	-2

c. *Wind speed*

Long term monthly average wind speed data were derived from regional weather stations that collected wind speed data. In southern Idaho, the nearest AgriMet station was used, and in central and northern Idaho a nearest NOAA airport weather station was used. Values varied by month.

Comparisons were made between daily ET from full cover alfalfa measured by lysimeter and reference ET estimated using dewpoint, solar radiation and wind speed data as described in steps a, b, and c. Results indicate that the estimation of these parameters tends to preserve the bulk variance of the original (measured) population of reference ET. Therefore, probability levels based on reference ET computed using these estimates are generally valid. Comparison of estimated vs. measured weather data at a number of AgriMet weather stations is detailed in Allen and Robison (2007) and indicated relatively good estimation accuracy. An example for daily and monthly estimation of solar radiation is shown in Figure 1 for the Picabo AgriMet weather station. Weather data for the 107 NWS stations used for ET_c were comprised of daily maximum and minimum air temperature and precipitation, along with observations of snowfall and snow cover depth (Figure 2). These data are officially collected and housed by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration.

Evapotranspiration from Crops and other Land Surfaces

The crop coefficient, K_c, has been developed over the past half-century to simplify and standardize the calculation and estimation of crop water use. The K_c is defined as the ratio of ET from a specific surface to ET_r. The specific surface can be comprised of bare soil, of soil with partial vegetation cover, or of full vegetation cover. The K_c represents an integration of effects of crop height, crop-soil resistance and surface reflectance that distinguish the surface from the ET_r definition and value. The value for K_c often changes during the growing season as plants grow and develop, as the fraction of ground covered by vegetation changes, as the wetness of the underlying soil surface changes, and as plants age and mature.

Two approaches to K_c have historically been applied in Idaho and elsewhere. The first approach uses a 'mean' K_c where all time-averaged effects of evaporation from the soil surface are averaged into the K_c value. The mean K_c represents, on any particular day, average evaporation fluxes expected from the soil and plant surfaces under some 'average' wetting interval (by rain or irrigation). The second K_c approach is the 'dual' K_c method, where the K_c value is divided into a 'basal' crop coefficient, K_{cb}, and a separate component, K_e, representing evaporation from the soil surface. The basal crop coefficient represents ET conditions when the soil surface is dry, but with sufficient root zone moisture present to support full transpiration. The K_e component is calculated separately, according to actual or simulated wetting events and is then added to the K_{cb} to produce the total K_c. Generally, a daily calculation time-step is required to apply the dual K_c method. This study applied the dual crop coefficient approach due to its ability to better quantify evaporation from precipitation and irrigation event.

Actual ET_c may be less than potential ET_c when soil water content is less than that able to sustain full rates of evapotranspiration. In this case, ET_c is reduced by applying a stress coefficient, K_s. The form of the equation for actual ET_c with the dual K_c approach is:

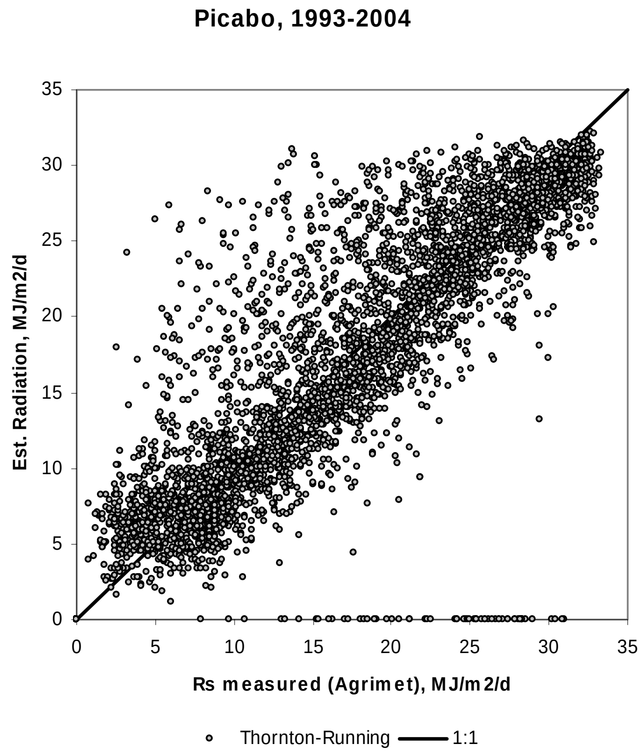
$$ET_{c\ act} = \left(K_s\, K_{cb} + K_e\right) ET_r \qquad (4)$$

where K_{cb} is the basal crop coefficient [0 - ~1.0 when used with ET_r], K_e is a soil water evaporation coefficient [0 - ~1.0 when used with ET_r], and K_s is a reduction coefficient that reduces the value of K_{cb} when the average soil water in the root zone is not adequate to sustain full plant transpiration. K_s = 1.0 when there is no water stress. All K terms are dimensionless.

The soil water balance incorporates the full effective root zone as simulated on a particular date during the growing season. A second and separate soil water balance is required to estimate K_e. In this latter water balance, only the water content of the upper 0.1 m of soil is simulated, since it is this upper soil layer that supplies water for direct evaporation from the soil surface. The daily water balance calculations and the calculation of K_s and K_e follow directly the procedure established in the FAO-56 publication (Allen et al., 1998) and extended by Allen et al., (2005). Departures from the Allen et al., (2005) procedure were made for the Idaho application to account for use of alfalfa reference ET_r rather than grass reference ET_o that is generally applied with the FAO-56 procedure. In addition, curvilinear K_{cb} curves similar to those used by Wright (1982) were used rather than the linear-style of curves generally used by FAO. Therefore, equations for estimating $K_{c\ max}$ and basal K_{cb} are different from those in the 2005 publication. When used with alfalfa ET_r, no weather-based adjustments to $K_{c\ max}$ nor K_{cb} are necessary.

The Crop Coefficient Curve. The crop coefficient curve represents the changes in K_c or K_{cb} over the course of the growing season, depending on changes in vegetation cover and maturation. During the initial period of the growing season, shortly after planting of annuals or after the initiation of new leaves for perennials, the value of K_{cb} is small, often only 0.1 to 0.15 for a dry soil surface (with some moisture at greater depth). When combined with soil evaporation, the total K_c value averages generally less than about 0.4 during the initial period. As the crop begins to develop more and more leaf area and cover more of the soil surface, the K_{cb} curve increases. Late in the growing season, the K_{cb} declines due to aging of leaves or senescence (dying) of leaves. A daily soil water balance is required to calculate K_s, since its value can change daily as soil water declines.

Examples of calculated K_{cb} and $K_{c\ actual}$ curves ($K_{c\ actual} = ET_{c\ actual} / ET_r$) are shown in Figure 3 for a crop of spring wheat and potatoes during the 2004 calendar year near Ashton, Idaho. The $K_{c\ actual}$ traces include the evaporation (K_e component) that appear as ‘spikes’ above the K_{cb} curves following precipitation and irrigation events. The $K_{c\ actual}$ during winter time peaked at about 0.6 for the spring wheat crop that was assumed to have a mulched soil surface during the nongrowing season. The $K_{c\ actual}$ reduced to about 0.4 when snow cover was present (January-February). Peaks in $K_{c\ actual}$ during winter were reduced when snow cover was noted to account for higher reflectance of the snow. $K_{c\ actual}$ was below K_{cb} when soil stress was estimated to occur during the nongrowing season or prior to initiation of irrigation (generally begun when $K_{cb} > 0.22$). The higher frequency of irrigation of potatoes (caused by a more shallow root zone than for the spring wheat crop) created more evaporation losses from the soil surface as evidenced by the large number of K_e ‘spikes’ above the K_{cb} curve. The duration of K_e spikes (time-wise) tends to increase during spring and fall as weather cools and more days are required to dry the soil surface. Even though the value estimated for $K_{c\ actual}$ was relatively high during the nongrowing season, the actual ET rate was relatively low (bottom of Figure 3) due to the low value for reference ET_r, which represents the drying power of the atmosphere and energy available for evaporation.



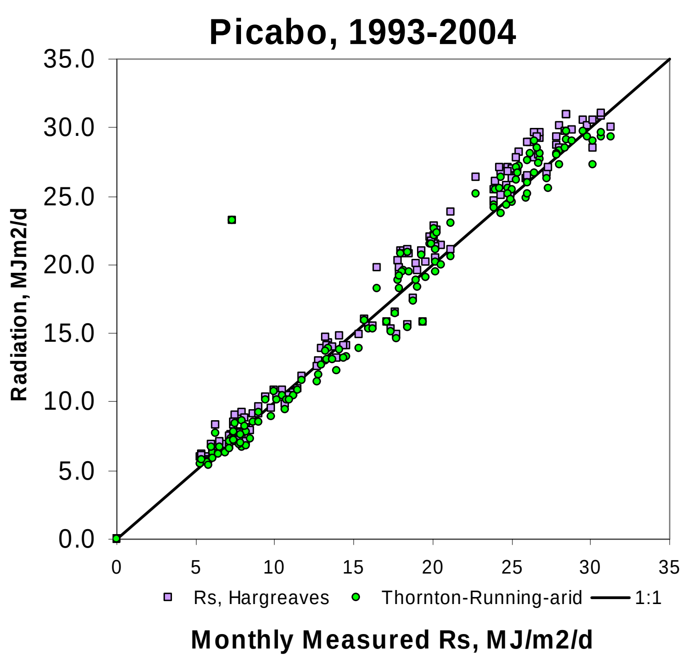


Figure 1. Daily estimated R_S (using the Thornton-Running (with Eq. 2a and 2b) (top) and monthly (bottom) vs. measured R_S from a nearby AgriMet station at Picabo, ID over the period of record.

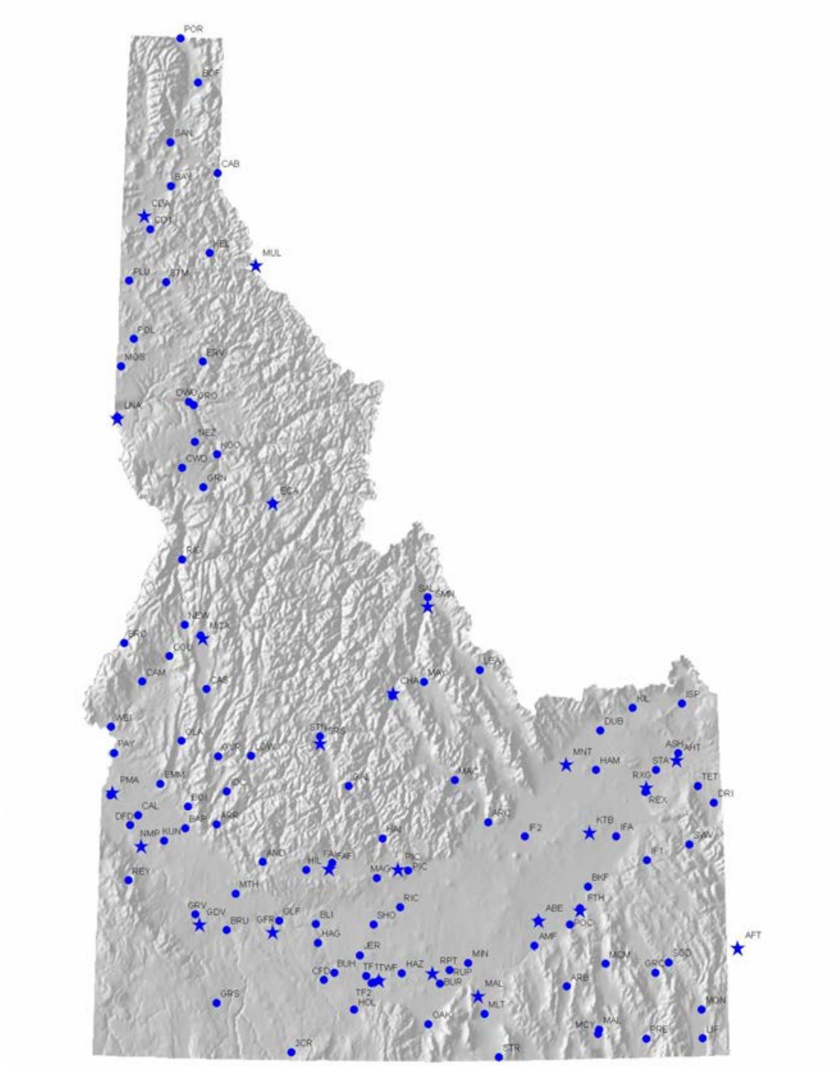


Figure 2. Locations of National Weather Service air temperature stations (circles) and AgriMet full weather stations in southern Idaho and airports used in north and central Idaho for wind (stars).

Application of K_{cb} Curves for a Variety of Locations and Periods of Record. In this study, starts and durations of growing seasons for most crops were determined year by year according to mean air temperature over 30-day periods prior to the start date and in proportion to growing degree days following the start of season. Growing seasons were terminated by estimated maturation date for the crop or by a killing frost. To allow K_{cb} curves to be 'stretched' differently each year, according to weather conditions, the base K_{cb} curves were expressed on relative time scales or relative thermal unit scales. Four different methods were used to express the base K_{cb} curves. These were 1) percent time from planting (or greenup) to harvest; 2) percent time from planting to effective full cover, with this ratio extended until termination; 3) percent time from planting to effective full cover and then days after full-cover; and 4) percent cumulative growing degree days from planting to effective full cover, with this ratio extended until termination. Basal crop coefficient curves were developed or organized for 42 crop and land-cover types. The K_{cb} curves of Wright (1982) that describe the eight most common crops in southern Idaho were converted to normalized cumulative growing degree days (NCGDD), which is method 4 above. K_{cb} values for sagebrush, cheatgrass and bunchgrass were developed based on vegetation index trends from Landsat images. The derived K_{cb} curves represent potential K_{cb} under conditions of readily available soil moisture. The K_{cb} values were reduced for nonirrigated vegetation or during nonirrigation periods using the K_s stress coefficient estimated from a soil water balance. All K_{cb} curves are described in Allen and Robison (2007).

Cumulative growing degree days (CGDD) since planting are commonly used as a basis for crop coefficient development (Sammis et al., 1985, Slack et al. 1996, Howell et al. 1997, Mitchell 1997, Snyder et al. 1999, Wright, 2001, deTar, 2004, Marek et al., 2006, Nebraska-HPCC, 2006) to adjust lengths of growth periods to account for variation in temperature among years and to facilitate transfer of crop coefficients among regions. Plant functions of growth, photosynthesis, water and nutrient absorption and transport, enzyme activity, and other biological and chemical activities are regulated by temperature. Thus, crop development is more closely related to the amount of heat the crop is exposed to than calendar days.

A wide range of computation methods for growing degree days (GDD) are in use. These include the standard method used for corn (maize):

$$GDD_{corn} = \frac{max(min(T_{max},30),10) + max(min(T_{min},30),10)}{2} - 10 \qquad (5)$$

where T_{max} is daily maximum air temperture, ^{o}C and T_{min} is daily minimum air temperature, ^{o}C. The standard corn equation is often referred to as a heat unit equation and is also known as the '86/50' method, referring to the maximum threshold of 30^{o}C and minimum threshold of 10^{o}C, which are 86 and 50 ^{o}F. The GDD equation for corn assumes no growth at air temperatures above 30^{o}C and no negative 'penalty' for growth if the minimum temperature goes below 10^{o}C.

A common, basic formula[4] for computing daily growing degree days (GDD) for most crops besides corn is to average daily maximum and daily minimum air temperatures for each day and subtract a minimum average daily temperature (base temperature) required for growth to proceed. There is no penalty applied when T_{max} exceeds a threshold, as is done with corn, and no 'boost' is given to T_{min} when it is lower than the minimum threshold, as is the case for corn. The basic equation for the general GDD is:

$$GDD = max\left(\frac{T_{max} + T_{min}}{2} - T_{base}, 0\right) \qquad (6)$$

where T_{base} is the base temperature. When T_{min} is far enough below T_{base} to cause the average daily temperature to go below T_{base}, then GDD = 0. Days having high T_{max}, but T_{min} below T_{base} are estimated by Eq. 6 to have lower growth rates than by Eq. 5, where T_{min} is 'boosted.' Wright (2001) suggested that Eq. 6 is realistic for many crops in semiarid climates such as Idaho, where cold nighttime temperatures can retard growth during daytime even when mid day temperatures are high. In the K_c curve conversion, Eq. 5 was applied to corn for consistency with standardized usage within the U.S. and Eq. 6 was applied to all other crops.

Winter Wheat. Winter wheat crops were simulated through the winter for purposes of estimating K_{cb} during winter. For winter wheat, some adjustments were made periodically to the CGDD that was accumulated since Oct. 1 to account for impacts of extremely cold weather that can retard growth for a few days or even 'burn' vegetation. In computing CGDD for the fall, winter and early spring periods for winter wheat, the following adjustments were made that apply to winter wheat only:

- Whenever T_{min} was < -25°C and there was no documented snow cover present, 10% of the established canopy was assumed to be frost burnt. This impact was enacted by reducing any CGDD accumulated since Oct. 1 for the winter wheat by 10% on the day following the low temperature.
- Whenever T_{min} was < -10°C then the GDD for the following day, if greater than 0, was reduced by 5 GDD units. This was done as a sort of retardation penalty to growth of winter wheat on the day after a cold freeze. GDD on all days was limited to 0 or greater.
- If T_{min} was < -4°C on a day, then GDD for that day was assumed to be zero, regardless of the value for T_{max} or T_{mean}. This was done as a sort of delay penalty to growth of winter wheat on the day of cold temperature. The no growth on days where T_{min} < -4°C is based on observations by (Wright, 2002, pers. comm.).

---

[4] For example, this formula is used by the Canola-Council (http://www.canola-council.org/gdd.aspx), Mitchell (1997) and Wright (2001).

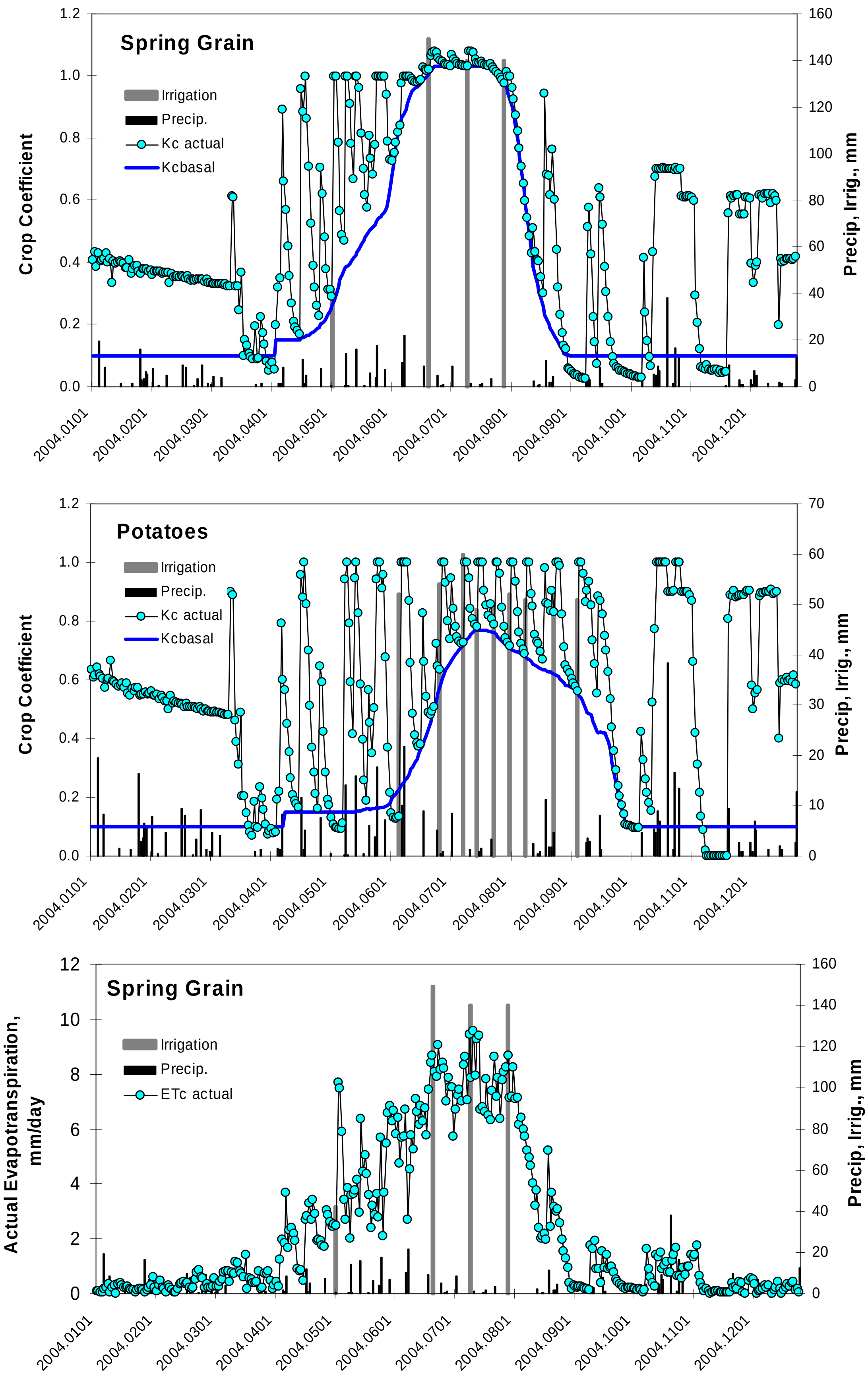


Figure 3. Example K_{cb} ('Kcbasal') and K_c actual curves for spring wheat and potato crops near Ashton, Idaho during 2004. Simulated irrigation events are shown as vertical bars. The K_c actual traces include the evaporation (K_e component) that appear as 'spikes' above the K_{cb} curves following precipitation and irrigation events. Also shown in the bottom figure is daily actual ET_c for the spring grain.

Normalization of Growing Degree Days. In normalizing the basis for K_{cb} curves, a normalized ratio NCGDD was calculated by dividing CGDD accumulated since planting (or greenup of alfalfa) by the $CGDD_{Planting\ to\ FC}$ where 'Planting to FC' is the period from planting to full cover. The NCGDD ratio is applied to the entire season or cutting cycle until either CGDD exceeds the value for $CGDD_{Planting\ to\ Terminate}$ that is in the table or a killing frost occurs. For alfalfa hay, K_c v. NCGDD curves were established for individual cuttings using data from Wright (1981, 1982) and lysimeter records for 1969-1971 period at Kimberly. Separate K_c vs. NCGDD were developed for the first growth period, for intermediate growth periods, and for the final growth period prior to frost. Unique K_c v. NCGDD shapes were established for these three periods. The NCGDD values for the first growing cycle are accumulated beginning at greenup of the crop in spring, and from the time of cutting for all subsequent growth cycles. Green up was estimated for alfalfa using CGDD since January 1 with temperature base of 0^oC. A CGDD of 240 ^oC-days from Jan. 1 was used to signal greenup, based on Kimberly data and observations across southern Idaho. No penalties were applied to CGDD of alfalfa as was the case for winter wheat. Figure 4 shows a summary of the K_{cb} curves of Wright (1982) after conversion to the NCGDD basis. NCGDD = 1.0 generally indicates the time of effective full cover.

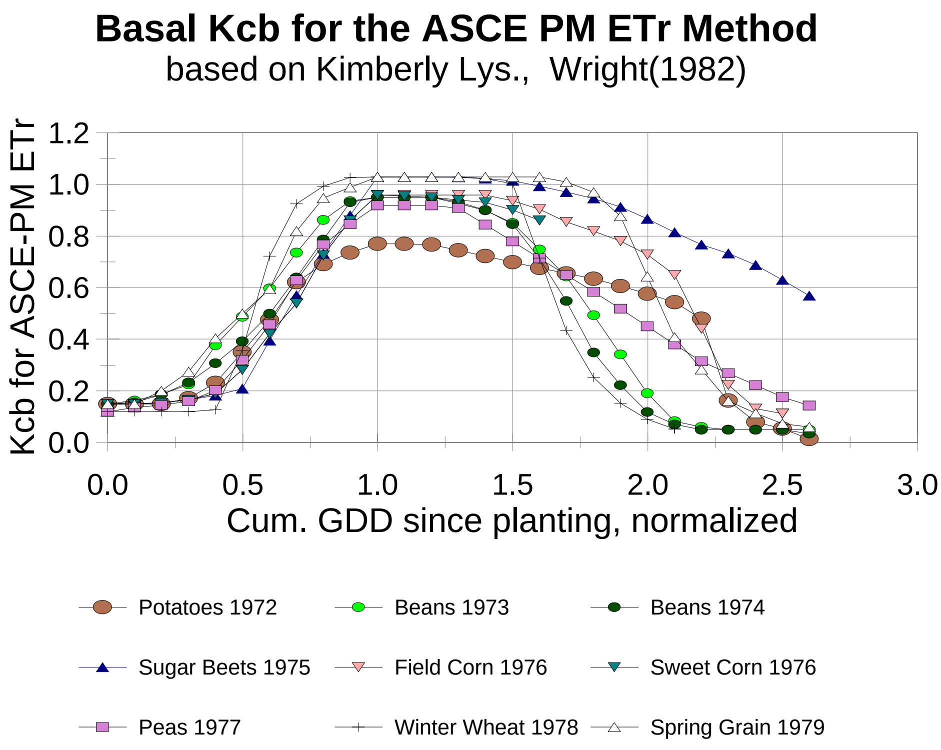


Figure 4. K_{cb} curves of Wright (1982) converted to the normalized cummulative growing degree-day basis (NCGDD).

Open Water Evaporation

Evaporation from open water was estimated for this Idaho study since water bodies are a common component of hydrologic systems and of irrigation supply systems. A special study of evaporation from the American Falls Reservoir was conducted by the University of Idaho during

2003-2005 where micrometeorological, Bowen Ratio and eddy covariance equipment was set up on the reservoir during one growing season (Allen and Tasumi, 2005). Measurements from that study were used to develop and calibrate aerodynamic procedures that were applied with air temperature data, only, to estimate evaporation from deep water bodies. In this study, evaporation was estimated for three classes of open water:

small, shallow stock ponds – K_c = 0.7 was used for all months

large, shallow water bodies or deep water bodies that have high turbidity – K_c = 0.6 for all months. This class may be generally applicable to *relatively shallow* (< 4 m in depth) *ponds, reservoirs and streams*

deep systems (relatively clear lakes and reservoirs deeper than 4 m) – use aerodynamic algorithms developed for American Falls Reservoir (Allen and Tasumi, 2005).

The evaporation estimates for small, shallow stock ponds were the highest of the three categories to account for the impact of generally shallower water on radiant energy absorption closer to the surface and thus generally higher surface temperature for these systems. In addition, shallow ponds tend to have more turbidity and thus higher surface temperature. The evaporation estimations assume that no freezing occurs. If water systems are known to freeze, then the evaporation rate will tend toward zero during the periods of ice cover.

Evaporation during Wintertime

Evaporation during nongrowing (wintertime) periods varies widely, based on availability of moisture, freezing of soils, snow cover, impacts of surface organic mulches (dead vegetation) and availability of energy for evaporation. Quantification of winter time evaporation is important when performing hydrologic water balances and when estimating effectiveness of wintertime precipitation in recharging the soil profile to supply water to vegetation during the subsequent growing season. Evaporation losses during winter, following soil wetting events, reduces the effectiveness of precipitation in recharging soil profiles.

Few studies have measured and documented wintertime evaporation. Wright (1991, 1993) conducted a series of wintertime measurements of evaporation using the dual precision weighing lysimeter systems at Kimberly. Figures 5 and 6 show mean K_c values derived by Wright (1991) that correspond to evaporation during nongrowing (winter) seasons at Kimberly over a six year period from 1985 – 1991. The lysimeter surface conditions included clipped fescue grass on one lysimeter that was dormant during the winter period and various 'bare soil' conditions on the other lysimeter representing soil conditions between annual agricultural crops. The bare soil conditions included disked wheat stubble, disked alfalfa, disked soil, alfalfa and winter wheat.

The basis for the mean K_c values in the figures is the ASCE-PM method. The ASCE PM alfalfa reference ET_r standard represents 0.5 m tall green alfalfa, even during winter (the crop is a hypothetical potential reference). Therefore, under even wet conditions, the K_c during winter time is not expected to reach 1.0. Mean K_c (K_{cm}) did approach or exceed 0.8 during Dec. 1988 - Mar. 1989 for the disked soil, a period having a nearly continuous distribution of precipitation. The data by Wright (1993) were used to guide the development of procedures for estimating wintertime evaporation for application throughout the state.

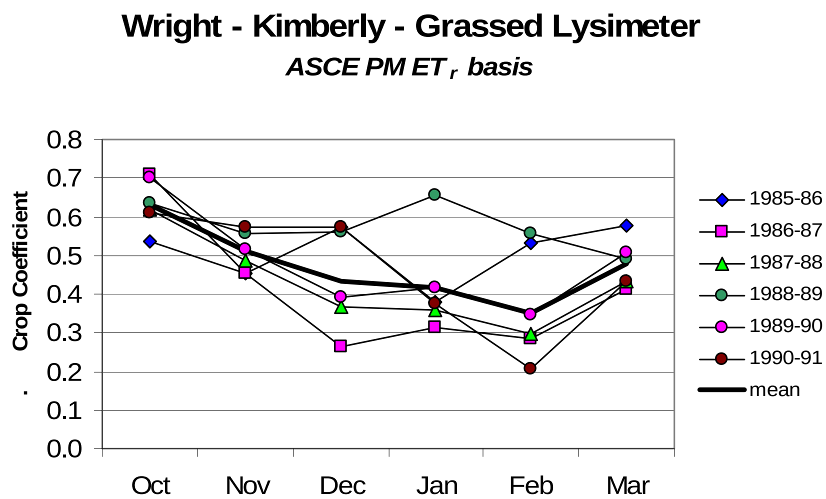


Figure 5. Mean monthly K_c measured by Wright (1993) from a grassed (dormant) lysimeter during nongrowing periods at Kimberly, Idaho converted for use with the ASCE Penman-Monteith alfalfa reference ET_r equation.

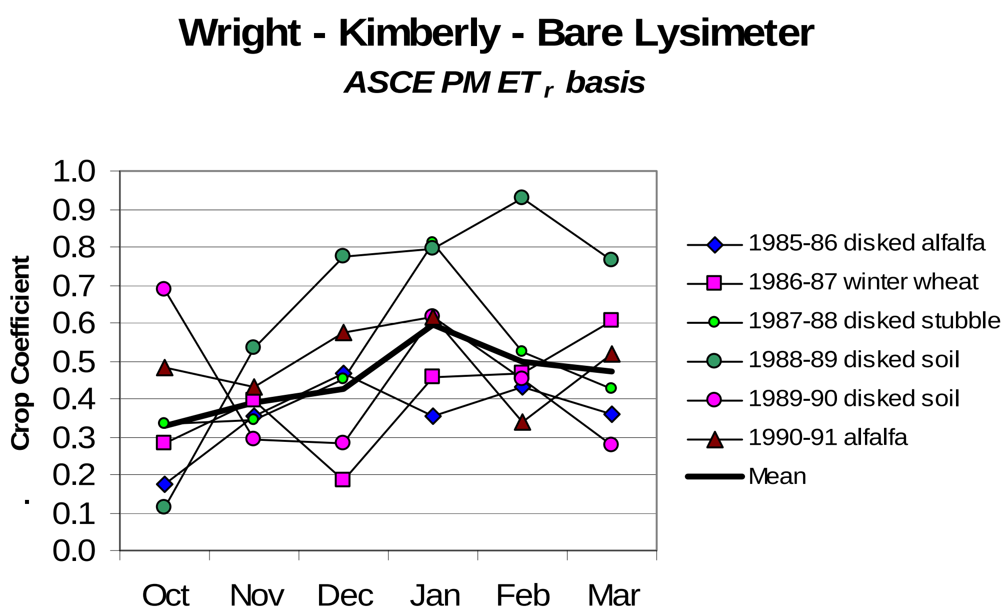


Figure 6. Mean monthly K_c measured by Wright (1993) during nongrowing periods at Kimberly, Idaho for various types of surface cover, converted for use with the ASCE Penman-Monteith alfalfa reference ET_r equation.

The nongrowing season (winter) period was defined as the period beginning at the end of a K_{cb} curve representing the growing cycle for a specific crop or the occurrence of a killing frost, and ending at greenup or planting of the same crop the following year (or Oct. 1 in the case of winter wheat). In estimating K_c for nongrowing season periods, a basal K_{cb} = 0.1 was used for bare soil conditions, for surfaces covered with some amount of mulch, and for dormant turf/sod systems. The K_{cb} represented conditions when these surfaces had a dry soil surface, but with sufficient moisture at depth to supply some diffusive evaporation. The evaporation (K_e) component was estimated separately in the daily soil water balance, where $K_{c\ max}$ during the nongrowing period was set at 0.9 for bare soil, 0.85 for mulched surfaces and to 0.8 for dormant grass cover. The lower value for grass is to account for insulative effects of the grass and higher albedo. The use of a low value for K_{cb} permits the K_e function in the daily calculations to increase the value for total K_c according to wetting frequency by rain and snow. An effective 'rooting zone' of 0.10 m was used for the fraction of surface under the cover. For all surfaces, a daily soil water balance was conducted and a stress coefficient is applied when soil water content drops below a critical value for the upper 0.10 to 0.15 m. Thus, actual K_c reduced below K_{cb} when both the ground surface and subsurface soil were dry. All land use types, including agricultural, landscape, horticultural and natural vegetation, were assigned one of the three winter cover conditions (dormant grass, bare soil or mulch classes) for estimating evaporation losses during winter.

Snow cover information was used to adjust the K_c ($K_{c\ max}$) value to account for higher albedo of snow and absorption of heat by melt by multiplying by a $K_{c\_multiplier}$. The following algorithms were applied:

$$K_{c\_multiplier} = 1 - K_{radiation\_term\_winter} + \frac{(1 - albedo_{snow})}{(1 - albedo_{surface})} K_{radiation\_term\_winter} \qquad (7)$$

where $K_{radiation\_term\_winter}$ represents the weighting of (or contribution to) winter time reference ET estimates by the radiation term of the Penman-Monteith method, $albedo_{snow}$ is the mean albedo of snow cover and $albedo_{surface}$ is the mean albedo of the bare surface. $K_{radiation\_term\_winter}$ is equivalent to:

$$K_{radiation\_term\_winter} = \frac{\Delta}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (8)$$

where Δ is slope of the saturation vapor pressure-temperature curve, γ is the psychrometric constant, r_s is surface resistance to vapor flow and r_a is aerodynamic resistance to heat and vapor flow above the surface. The intent of Eq. (7) is to adjust the ET_r estimates by the Penman-Monteith method, which is parameterized to estimate ET for a vegetated surface to those that would have occurred from snow cover. The primary adjustment is for albedo of the surface, which is higher for snow cover. For ease of calculation, $K_{radiation\_term\_winter}$ was calculated as a function of day of year based on a relation derived using full years of Kimberly weather data and the ASCE standardized Penman-Monteith equation:

$$K_{radiation\_term\_winter} = 2.2E-08\ J^3 - 2.42E-05\ J^2 + 0.006\,J + 0.011 \quad (9)$$

An additional reduction in evaporation of 30% was made to account for absorbed latent heat of fusion of any melting snow prior to evaporation. Albedo of snow was set at 0.8 in calculations and albedo of the surface was set to 0.25.

Estimating Beginning and End of Growing Seasons

The greening (greenup) of perennial vegetation in spring can be strongly impacted by short-term weather conditions, primarily by air temperature and to some degree by wetting events and general amounts of solar radiation. Strong correlation exists between air temperature, wetness and cloudiness and in general, air temperature can be used as a predictor of when perennial vegetation begins to greenup in spring. In the same manner, planting dates for annual crops are impacted by general temperature conditions. Planting is strongly influenced by soil temperature at seed depth and some relationships have been established for some crops. However, soil temperature is not commonly measured at cooperative NWS weather stations and is available at regional types of stations only. Therefore, 30-day average mean daily air temperature has been used as a surrogate for soil temperature due to the strong correlation between soil temperature and air temperature over an extended period.

The use of a thirty-day running average mean air temperature (T_{30}) to estimate planting of annual crops was investigated using the lysimeter and cropping records at Kimberly, Idaho. The use of 30-day average temperature is similar to that of the SCS TR-21 (1967) where that publication listed typical mean monthly values for air temperature to signal planting and greenup of crops. However, some of those dates, for example, for alfalfa green up do not estimate well for Idaho. The T_{30} temperatures from SCS TR-21 were for dates centered on the 30 day periods, rather than for dates at the end of the 30 day periods, as used in this study. Specific values by Allen and Robison (2007) are listed in Table 2.

Table 2. 30-day mean air temperatures (for the 30-day period prior to the noted date) for Magic Valley crops associated with Wright (1982) dates for lysimeter crops, and also associated with Allen-Brockway (1983) planting dates and from field notes taken by Allen (pers. comm.) between 1999 and 2005, and comparisons with SCS TR-21.

Crop	Year	Plant Date	30-day T (C) ending on date	Equiv. 37 yr ave. date	Recomm. T_{30} to use, °C	Mean date over 37 yr. for Recommended T_{30}	TR-21 T_{30m}*, °C
based on Wright (1982):							
Barley or S.Wht	1979	4/1/79	4.8	4/3	4.7	4/2	7
Peas	1977	4/10/77	4.4	3/31	5	4/4	
S.Beets	1975	4/15/75	2.1	3/12	5 (8)**	4/4 (for 5°C)	-2 frost
Potatoes	1972	4/25/72	6.0	4/14	7	4/20	16
Corn	1976	5/5/76	7.9	4/29	8 (10)**	4/29 (for 8°C)	13
Beans	1973 1974	5/22	12.5 12.3	5/30	12 (14)**	5/27 (for 12°C)	16
based on Allen-Brockway (1983):							
Pasture	Mean	4/3	4.8		5	4/4	7
Orchards	Mean	4/15			6	4/13	10
Veges.	Mean	5/20			10	5/14	
Onion	Mean	4/20			6.5	4/17	

* The 30 day mean T_{30} value for TR-21 is for the period centered on the date, thus, $T_{30m} > T_{30}$.

** The value in parentheses was used in Allen-Robison (2007) calculations based on comparisons with METRIC results over the Magic Valley area of southern Idaho for year 2000 and based on other local observations of planting dates across southern Idaho.

During the estimation of planting or greenup dates for crops and natural vegetation, a “no earlier than” and “no later than” date was used to constrain the estimated dates to within realistic ranges based on expected behavior of farmers or the vegetation itself. For most crops this was +/- 40 days from the mean date based on a longterm average temperature. For alfalfa, better consistency in estimation of greenup in spring was found using cumulative growing degree days (CGDD) since January 1 rather than T_{30}. Based on a CGDD analysis of daily ET and leaf area and height development data for alfalfa for years 1969-1971 by Wright at Kimberly, CGDD = 240 °C using a 0°C GDD basis was used to estimate greenup.

Adjustment of K_{cb} for Alfalfa During the Fall

For alfalfa, an additional adjustment was made to the computed K_{cb} during fall periods to account for effects of cold nighttime temperatures and occaisional light, but nonkilling frosts. The adjustment reduced the value for K_{cb} following the first occurrence of a -3^{o}C in the fall by 0.005 each day following the -3^{o}C temperature. This reduced the value for K_{cb}, for example, by 0.10 by the 20th day following the light frost. The killing frost temperature for alfalfa was -7^{o}C. Allen and Robison (2007) contain estimated killing frost temperatures for a wide range of crops and vegetation.

Comparison of Crop Evapotranspiration Products with Other Sources

Illustrative comparisons were made between seasonal ET_c calculated for this study and that reported by USBR AgriMet ET_c for 2000. Comparisons were also made with seasonal ET reported by Allen et al. (2007b) for crops in Magic Valley during year 2000 as determined using the METRIC satellite-based energy balance processing system (Allen et al. 2007a). Growing season ET_c is compared in Figure 7 for weather stations located near Twin Falls and Jerome, which are 30 km apart. The year 2000 was the focus of an intensive application of the METRIC satellite-based energy balance method for estimating ET over large areas. METRIC estimates actual ET for specific fields of crops using short wave and thermal images from the Landsat satellite.

The values shown for METRIC in Figure 7 were sampled from large numbers of fields in the Jerome and Twin falls counties from METRIC ET images of ET (and K_c) between the dates of March 15 and October 17 (Tasumi et al., 2005, Allen et al., 2007c). The METRIC derived images were integrated monthly and over the March 1 – October 31 period. The ‘Allen-Robison (2007)’ entries in Figure 7 represent ET_c determined in this study for the March-October 2000 period and are presented for ET_c calculations based on the Twin Falls 7E and Jerome NWS weather stations as well as based on data from the Twin Falls AgriMet weather station. The Twin Falls AgriMet weather station is collocated with the Twin Falls 7E NWS station at the USDA-ARS center near Kimberly. The ‘Allen-Robison’ ET_c calculations for the AgriMet station were made using reference ET_r based on a full complement of AgriMet weather data (solar radiation, air temperature, humidity and wind speed) whereas the Twin Falls 7E NWS ET_r calculations were based on daily air temperature and long-term mean monthly wind speed only. The ‘AgriMet – Twin Falls – 2000” entry in Figure 7 represents growing season ET_c reported by the USBR AgriMet web site.

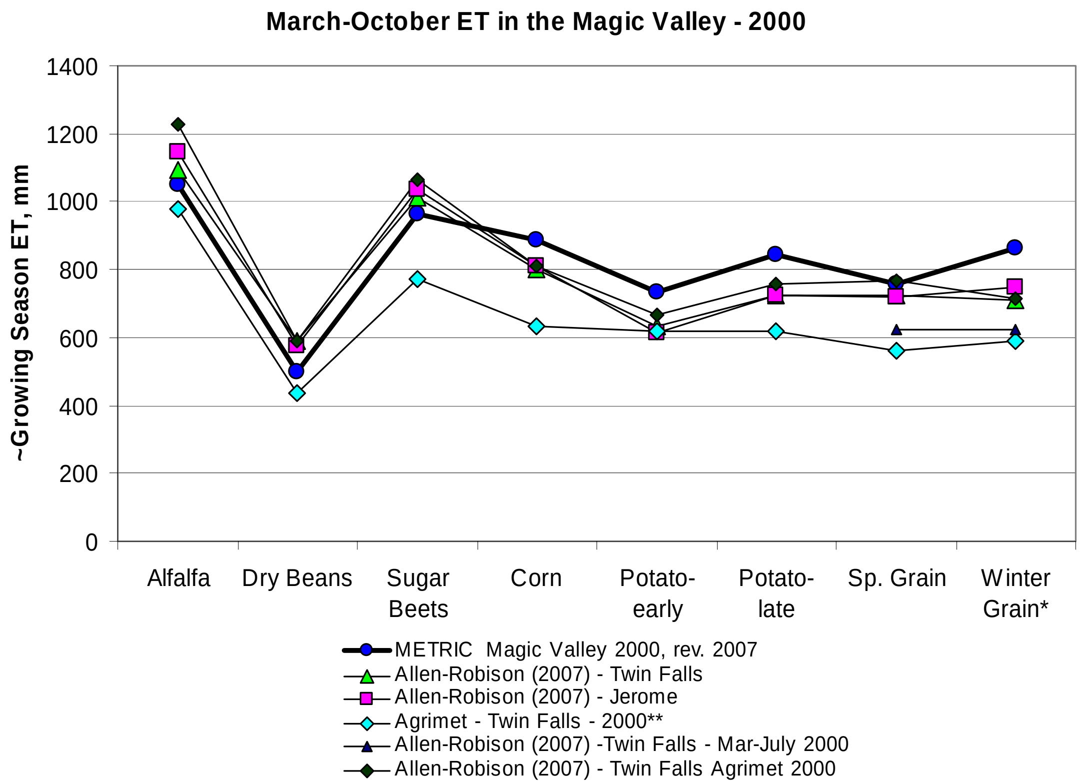


Figure 7. Growing season evapotranspiration during year 2000 for major crops grown in the Twin Falls – Jerome area of Magic Valley from four sources (1. METRIC satellite-based energy balance; 2. this study for Twin Falls 7E and Jerome NWS stations; 3. USBR AgriMet ET reports; and 4. this study using the Twin Falls AgriMet station data). The smaller triangles represent ET_c summed for spring and winter grain for the March – July 2000 period only.
**The AgriMet Twin Falls - 2000 entries were taken from the USBR AgriMet web site for year 2000 and represent calculations by the USBR.

The growing season ET_c from the new (Allen-Robison 2007) computations compared relatively closely with that determined by METRIC for alfalfa hay, sugar beets and spring grain. The new computations exceeded those by METRIC by a small amount for alfalfa hay, dry beans and sugar beets. The new computations were lower than those by METRIC for corn, early and late potatoes and winter grain. Growing season ET_c from the new computations (average of Twin Falls and Jerome stations) was within 7% of METRIC estimates for alfalfa hay, sugar beets and spring grain and all were within 16% of METRIC ET_c. The new estimates averaged about 16% above METRIC estimates for dry beans and 15-16% below METRIC estimates for winter grain and potatoes.

Reasons for the lower ET_c estimation by Allen-Robison (this study) for corn and potatoes, relative to METRIC may stem partly from the assumption of relatively low-frequency irrigation scheduling when simulating irrigation schedules during this study for estimation of soil evaporation. Corn crops tend to be irrigated by center pivot systems and potato crops by center pivots or by solid set sprinkler. Both of these system types tend to be operated so that irrigations are spaced more closely together in time than for wheeline or gravity systems. The consequence of this is more frequent wetting of the soil surface and somewhat higher total ET_c. This may explain some of the 10 to 15% difference between the two estimating approaches (this report vs. METRIC). The 16% underestimation for ET_c of winter wheat as compared to METRIC-produced ET_c appears to stem primarily from estimation of earlier crop development during early spring and earlier maturity and harvest in this study for year 2000 than observed by METRIC.

The AgriMet ET_c that was produced by USBR-AgriMet estimated about 7% below METRIC-derived growing season ET_c for alfalfa hay and 13-15% below METRIC for dry bean and early potato crops. AgriMet ET_c estimated 20-30% below METRIC for the balance of crops (sugar beets, corn, late potatoes, spring grain, winter grain). Agrimet estimated shorter growing periods for sugar beets and field corn, as reflected in the K_c curves for Magic Valley than observed by METRIC and earlier growing periods for winter and spring grain. An additional reason for the lower seasonal ET_c estimates by AgriMet is that their ET_c calculations do not begin until emergence (or greenup) and are discontinued at estimated harvest for annual crops. Therefore, evaporation from precipitation prior to and following the specific growing periods is neglected.

Runoff from Precipitation

Runoff during precipitation events is strongly influenced by soil texture, soil structure, sealing and crusting of the soil surface, land slope, local land forming (tillage and furrowing), antecedent moisture, precipitation intensity and duration. Generally, estimation of runoff during precipitation is fraught with uncertainty. For general purposes, runoff in this study was estimated using the USDA-NRCS Curve Number approach (USDA-SCS 1972), where antecedent soil moisture conditions were estimated in conjunction with the daily soil water balance used in estimating the soil water evaporation coefficient, K_e. Required data are daily precipitation.

Statistics and Time Series

Besides the daily, monthly and annual time series of ET_c that have been compiled, tables of statistics describing 30-year normals (means) for ET_c on monthly, growing season and annual bases have been developed. These tables include means, standard deviations and 20 and 80% exceedence values that describe the expected variation within the populations of ET_c. The statistics were computed for time period lengths of 3, 7, 15 and 30 days within each month. These period lengths were selected to encapsulate expected lengths of irrigation intervals or drying periods that are of interest in irrigation system design and operation.

The statistics were computed over the most recent 30 years of valid (nonmissing) data or over shorter periods if less than 30 years of valid data were available. The 30 year normal periods were used to generate statistics describing the behavior of the ET data rather than the entire periods of record for two reasons. One, lengths of records varied widely from station to station, ranging from as few as eight years at Magic Dam east of Fairfield (1966-1975) to 111 years at Oakley (1893-2004). Secondly, some trends in air temperature and consequently ET estimates have occurred over long periods of time. Some of these trends are caused by changes in relative dryness of the local or regional environment due to irrigation development or land-use change, by station location or relocation, or perhaps by change in overall climate. The last 30 years of usable record are considered to be the more representative of expected future conditions than prior periods. The full records for each station are preserved in the daily, monthly and annual time series files. Therefore, statistics for the full periods of record can be computed as needed from these series.

Time series and statistics have been compiled for the following four basic ET or precipitation parameters: a) actual evapotranspiration; b) potential evapotranspiration; c) basal evapotranspiration; and d) precipitation deficit (i.e., net irrigation water requirement). Actual ET values lie below potential ET values during periods of soil moisture stress in rainfed conditions, during nongrowing periods and occaisionally early in growing seasons prior to initiation of irrigation. The basal ET values represent ET when little or no free water evaporation from the soil surface occurs. The precipitation deficit represents the amount of (irrigation) water beyond any effective precipitation needed to sustain the potential ET rates. The new calculations for ET_c tend to agree with growing season totals presented by Allen and Brockway (1983) for primary agricultural crops and as observed by the METRIC satellite-based ET procedure.

REFERENCES

Allen, R.G. and C. E. Brockway. 1983. Estimating Consumptive Irrigation Requirements for Crops in Idaho, Research Technical Completion Report, Idaho Water and Energy Resources Research Institute, University Idaho, Moscow, ID 130 pages.

Allen, R.G. and C.W. Robison. 2007. Evapotranspiration and net irrigation water requirements for Idaho. Univ. Idaho reported submitted to Idaho Dept. Water Resources. 245 p. www.kimberly.uidaho.edu/ETIdaho.

Allen, R.G. and M. Tasumi. 2004. Evapotranspiration from Riparian Vegetation along the Middle Rio Grande Basin using METRIC™ ET Products. Report to Keller-Bliesner Engineering. University of Idaho Kimberly Research and Extension Center. 18 p.

Allen, R.G. and Tasumi, M.. 2005. Evaporation from American Falls Reservoir in Idaho via a Combination of Bowen Ratio and Eddy Covariance. Proceedings of the EWRI World Water and Environmental Resources Congress 2005: Impacts of Global Climate Change. May 15-19, 2005, Anchorage, Alaska, USA , 17 p.

Allen, R.G. and J.L. Wright. 2002 and 2006. Conversion of Wright (1981) and Wright (1982) alfalfa-based crop coefficients for use with the ASCE Standardized Penman-Monteith Reference Evapotranspiration Equation. Unpublished Univ. of Idaho report. 51 pages.

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman. 1989. “Operational estimates of reference evapotranspiration.” *Agron. J.*, 81:650-662.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. *"Crop Evapotranspiration: Guidelines for computing crop water requirements."* Irrig. and Drain. Paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 pp.

Allen, R.G., L.S. Pereira, M. Smith , D.Raes , and J.L. Wright. 2005. FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions. *J. Irrig. and Drain. Engrg.*, ASCE 131(1):2-13.

Allen, R.G., M. Tasumi and R. Trezza. 2007a. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. ASCE *J. Irrigation and Drainage Engineering* (in press).

Allen, R.G., M. Tasumi, A.T. Morse, R. Trezza, W. Kramber, I. Lorite and C.W. Robison. 2007b. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Applications. ASCE *J. Irrigation and Drainage Engineering* (in press).

Allen, R.G., M. Tasumi, J.L. Wright, R. Trezza, I. Lorite, C. Robison. 2007c. Satellite-based ET mapping for agricultural water management: Estimating evapotranspiration by NDVI. In preparation for submission to *Ag. Wat. Man.*

ASCE – EWRI. (2005). The ASCE Standardized reference evapotranspiration equation. ASCE-EWRI Standardization of Reference Evapotranspiration Task Comm. Report, available at http://www.kimberly.uidaho.edu/water/asceewri/

BOR. 2005. AgriMet; The Pacific Northwest Cooperative Agricultural Weather Network, Bureau of Reclamation. Internet Article: http://137.77.133.1/pn/AgriMet/ (visited Feb. 2005).

DeTar, W. R. 2004. Using a subsurface drip irrigation system to measure crop water use. Irrigation Science 23(3): 111-122.

Hargreaves, G.H. and Z.A. Samani. 1982. "Estimating potential evapotranspiration." Tech. Note, *J. Irrig. Drain. Engrg.*, ASCE, 108(3):225-230.

Hargreaves, G.L., G.H. Hargreaves, and J.P. Riley. 1985. "Agricultural benefits for Senegal River Basin." *J. Irrig. Drain. Engrg*., ASCE 111:113-124.

Howell, T. A., Steiner, J. L., Schneider, A. D., Evett, S. R., and Tolk, J. A. 1997. "Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn-Southern High Plains." Trans. ASAE, 40(3), 623–634.

Jensen, M.E., R.D. Burman, and R.G. Allen (ed). 1990. *"Evapotranspiration and Irrigation Water Requirements."* ASCE Man. and Rep. on Engineering Pract. No.70, NYork, 332 p.

Marek, T., P. Colaizzi, T.A. Howell, D. Dusek, and D. Porter. 2006. Estimating seasonal crop ET using calendar and heat unit based crop coefficients in the Texas High Plains Evapotranspiration Network. ASABE Pap. no: 062206, 2006 ASABE Ann. Int. Mtg, Portland, Oregon, 9 - 12 July 2006, 11 p.

Mitchell, A.R.. 1997. Irrigating Peppermint. Oregon State Univ. Extension Service. EM 8662

Nebraska High Plains Climate Center. 2006. Crop Coefficients, Phenology, and Growing Degree Day Accumulation. http://www.hprcc.unl.edu/crop/

Sammis, T. W., Mapel, C. L., Lugg, D. G., Lansford, R. R., and McGuckin, J. T. (1985). "Evapotranspiration crop coefficients predicted using growing degree days." Trans. ASAE, 28(3), 773–780

Slack, D. C., Martin, E. D., Sheta, A. E., Fox, F. A., Jr., Clark, L. J., and Ashley, R. O. (1996). "Crop coefficients normalized for climatic variability with growing-degree-days." Proc., International Conf., Evapotranspiration and Irrigation Scheduling, San Antonio, Tex., C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., Am. Soc. Agric. Engr., St. Joseph, Mich., 892–898.

Snyder, R. L., Spano. D., Cesaraccio, C., and Duce, P. 1999. "Determining degree-day thresholds from field observations" Int. J. Biometerology, 42:177-182.

Tasumi, M., R. G. Allen, R. Trezza, J. L. Wright. 2005. Satellite-based energy balance to assess within-population variance of crop coefficient curves, *J. Irrig. and Drain. Engrg,* ASCE 131(1):94-109.

Thornton, P.E. and S.W. Running. 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. *Agricultural and Forest Meteorology* 93:211-228.

Todd, R.W., S.R. Evett, and T.A. Howell. 2000. The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment. *Agric. Forest Meteorol*. 103(2000):335-348.

USDA, 1967. Irrigation Water Requirements. USDA Soil Conservation Service Tech. Release 21 (Rev. 1). 88 p.

USDA-SCS. 1972. National Engineering Handbook, Section 4, Table 10.1.

Wright, James L. 1981. "Crop Coefficient for Estimates of Daily Crop Evapotranspiration." *Proc. Am. Soc. Agric. Engrs., Irrig. Scheduling Conf*., Dec. 1981, pp. 18-26.

Wright, J.L. 1982. "New Evapotranspiration Crop Coefficients." *J. Irrig. and Drain. Div.*, ASCE, 108:57-74.

Wright, J.L. 1988. Daily and seasonal evapotranspiration and yield of irrigated alfalfa in southern Idaho. *Agron. J*. 80:662-669.

Wright, James L. 1991. Using weighing lysimeters to develop evapotranspiration crop coefficients. pp. 191-199. In: R.G. Allen, T.A. Howell, W.O. Pruitt, I.A. Walter & M.E. Jensen (eds.). Proc. of the International Symposium on Lysimetry, July 23-25, Honolulu, Hawaii. ASCE, 345 E. 47th St., New York, NY 10017-2398.

Wright, James L. 1993. Nongrowing season ET from irrigated fields. p. 1005-1014. In: R.G. Allen and C.M.U. Neale (eds.) Management of Irrigation and Drainage Systems: Integrated perspectives. Proc. Workshop ASCE Irrigation and Drainage Division, Park City, UT, 21-23 July, 1993

Wright, J.L. 2001. Growing degree day functions for use with evapotranspiration crop coefficients. CD-ROM. American Society of Agronomy. *Agronomy Abstracts.*

Wright, J.L. and M.E. Jensen. 1972. "Peak water requirements of crops in Southern Idaho." *J. Irrig. and Drain. Div.*, ASCE, 96(ir1):193-201.

Wright, J.L., R.G. Allen, and T.A. Howell. 2000. "Conversion between evapotranspiration references and methods." p. 251-259, *Proc., 4th Decennial National Irrigation Symp.*, Phoenix, AZ , ASAE, St. Joseph, MI.

MEASURING AND ESTIMATING OPEN WATER EVAPORATION IN ELEPHANT BUTTE RESERVOIR IN NEW MEXICO

A. Salim Bawazir[1]
Zohrab Samani[2]
Max Bleiweiss[3]

ABSTRACT

Elephant Butte Reservoir with an estimated surface area of 40,000 acres at full capacity is considered a major component of the Rio Grande hydrology. Understanding evaporative loss from the reservoir is needed for management and distribution of the Rio Grande water among various users. An eddy covariance tower is currently measuring the evaporation rate in a localized area of the reservoir. However, evaporation is highly variable across the Reservoir's water surface. This paper describes a methodology to account for spatial and temporal variability of the evaporation from reservoir using a combination of remote sensing and ground measurement.

INTRODUCTION AND BACKGROUND

The Elephant Butte Reservoir (EBR) is a vital part of the management and distribution of water to southern New Mexico, Texas and Mexico. Increasing demand for water due to population growth coupled with recent drought has prompted water management agencies to determine better methods of assessing evaporation losses from the Reservoir. Currently, evaporation losses are estimated from a single evaporation pan placed near the dam at the southern end of the reservoir. This elevation can be significantly higher than the reservoir water surface, especially during periods of lower-than-average storage. Stage-surface-area tables developed from periodic hydrographic surveys are used to relate the point measurement of evaporation to the volume of water lost from the Reservoir. A mean annual rate of 9.74 ft/yr was reported by Farnsworth et al. (1982) from EBR's Class A pan evaporation data compiled from 1956 though 1970. However, evaporation studies performed on other deep relatively clear reservoirs in the western United States have found reservoir evaporation to be considerably less than pan evaporation and reference evapotranspiration (Allen and Tasumi, 2005). This is attributed to the large amounts of heat storage from solar radiation penetrating the water surface. The solar energy stored instantaneously as heat in the water body itself is not immediately available for the evaporation process. It is only available to the surface energy budget when transferred there by conduction or convection.

Remotely sensed surface temperature of the EBR Advanced Thermal Emission and Reflection Radiometer (ASTER) has shown the variability of surface temperature on spatial and temporal

[1]Assistant Professor, Civil Engineering Department; New Mexico State University, MSC 3CE, Box 30001, Las Cruces, NM 88003; abawazir@nmsu.edu
[2]Professor, Civil Engineering Department; New Mexico State University, MSC 3CE, Box 30001, Las Cruces, NM 88003; zsamani@nmsu.edu
[3]Science Specialist, Entomology, Plant Pathology and Weed Science Department, MSC 3BE, Box 30003, Las Cruces, NM 88003; mbleiwei@taipan.nmsu.edu

scale (figure 1). The image is color-coded to show variation in surface temperature (upper portion) while the graphs in the lower portion show the distribution of water temperature over the lake. This paper describes a methodology to account for spatial and temporal variability of the evaporation from reservoir using a combination of remote sensing and ground measurement.

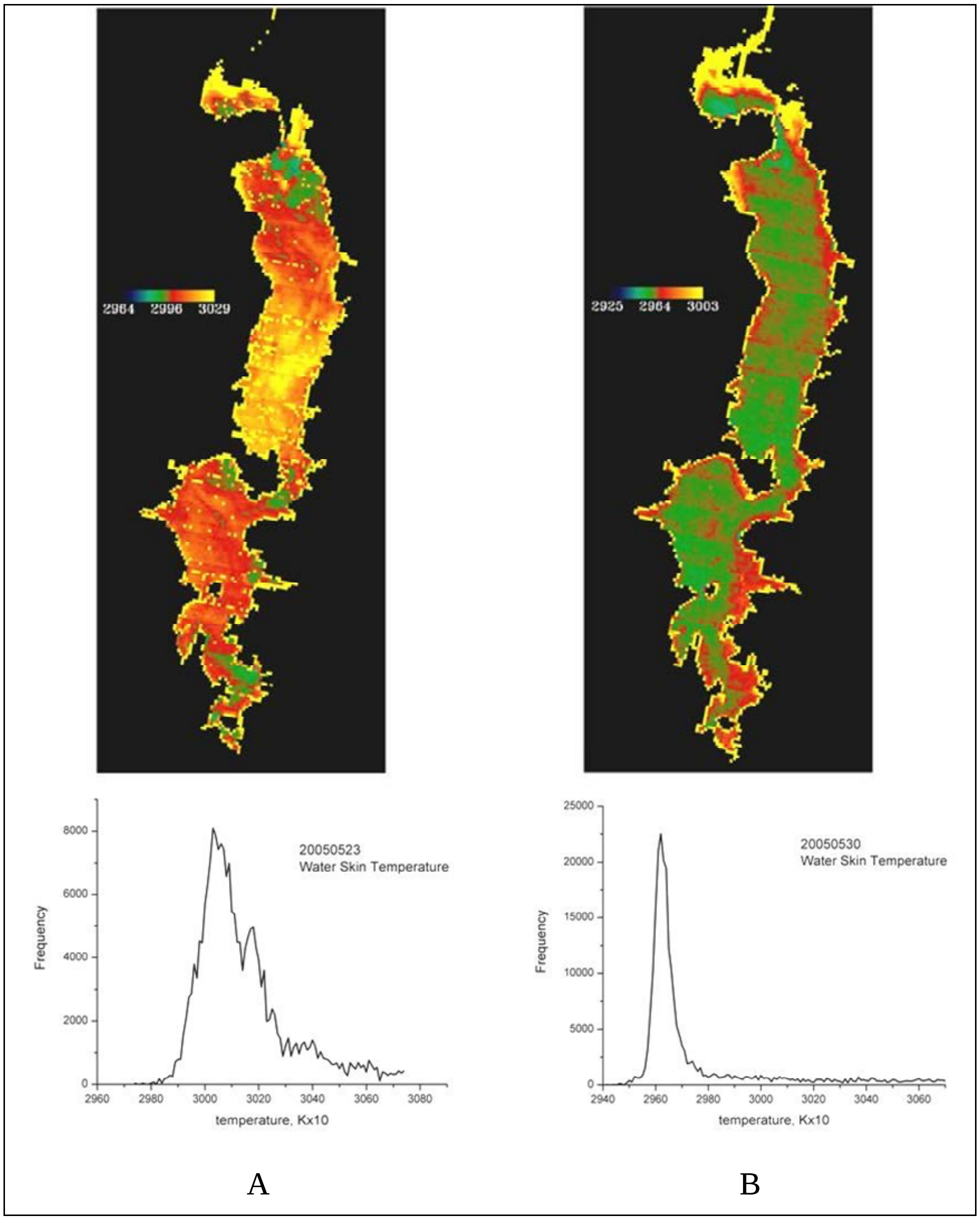


Figure 1. Satellite (ASTER) temperature results showing the spatial distribution of surface water temperature in (A) May 23 and (B) May 30 of 2005. The units of the scale are K x 10.

Elephant Butte Reservoir Description and Location

The Elephant Butte Reservoir on the Rio Grande is located (Lat 33:09:15N; Long 107:11:28W, NAD27) in south central New Mexico. The reservoir was constructed from 1911 to 1916 with a capacity of 2,638,860 acre-ft in order to control downstream flooding, provide water for irrigation from the Rio Grande to the south valleys of Rincon and Mesilla, make deliveries to Texas and Mexico, and later for hydroelectric power generation. At full capacity, the reservoir extends to approximately 40 miles long and its width varies from 2 to 4 miles, covering a surface area of 40,000 acres (Scurlock, 1998). It was reported by Gunaji (1968) as having a capacity of 2,194,990 acre-ft and covering a surface area of approximately 36,580 acres at a spillway of 4407 ft. The decrease in capacity was attributed to accumulation of sediments. A most recent unpublished report (U.S. Bureau of Reclamation, 2005) on storage and surface area stated that from January through December 2005 the reservoir storage ranged from 241,740 to 558,720 acre-ft, with corresponding surface areas of 8,673 and 13,748 acres at stages of 4309.94 and 4344.04 ft, respectively. It is considered normal for the reservoir stages to fluctuate 15 to 30 ft annually.

Remotely Sensed Data

Surface temperature or skin temperature of the reservoir could be obtained with reasonable accuracy remotely e.g. satellite. For example, the ASTER five-channel multispectral thermal-infrared (TIR) scanner were compared to ground measurements of skin-temperature of water at Elephant Butte Reservoir in New Mexico. Skin temperature of water was measured using precision infrared sensor model IRTS-P (Apogee Instrument Inc., Logan, UT). The sensor was installed on an extended horizontal arm of approximately 1 m from an off-shore triangular tower in deep water (figure 2). The infrared sensor was maintained at an average height of less than 1 m above the water surface. Preliminary results indicated a good comparison. The comparison of "surface" measured skin temperature to satellite estimated surface temperature during the clear days of May 23rd and 30th, 2005 show that ASTER under estimated skin temperature by only 0.31 K and 0.44 K, respectively.

Ground measurements

A 115 ft off-shore tower using eddy covariance system (Campbell Scientific Inc., Logan, Utah) was installed in the reservoir to monitor fluxes. Micrometeorological sensors measuring wind velocity and direction, air temperature and relative humidity were also installed. Two basic weather stations located at the north and south ends of the Reservoir were used to collect land-based meteorological data such as ambient temperature, humidity, solar radiation, wind speed and direction, and precipitation.

Figure 2. Infrared sensor model IRTS-P above water surface at Elephant Butte Reservoir

METHODOLOGY

The bulk-aerodynamic method has been used successfully to estimate evaporation from Lakes Mead and Hefner (Harbeck, 1962) using fairly simple instrumentation. Despite successful estimates at Lakes Mead and Hefner, estimating evaporation losses over entire reservoirs is still a challenge. The bulk-aerodynamic method can be used to estimate sensible heat and latent heat fluxes through a fixed boundary layer such as that developed over the free water surface of a reservoir. It is based on the concept of mass transfer theory, which states that the diffusion of heat and water vapor into the atmosphere moves from where its concentration is larger to where its concentration is smaller at a rate that is proportional to the spatial gradient of that concentration (Dingman, 2002). This is similar to the coefficients of heat and vapor transfer. This method is simple because it relies on relatively routine measurements of wind speed, air temperature, relative humidity, and water surface temperature. However, this method has been used for point measurements to estimate the entire water body surface. Using the same concept, the bulk-aerodynamic method combined with Monin-Obukhov stability function (Monteith and Unsworth, 1990) solved iteratively using ground and remotely sensed data, could be used to better estimate evaporation of the entire reservoir.

Assuming that the boundary layer over a smooth water surface is similar to that over a rough water surface, Kondo (1975) presented the following expressions of bulk-aerodynamic method for sensible and latent heat fluxes:

$$H = C_H \cdot c_p \cdot \rho_a \cdot u_z \cdot (T_s - T_a) \tag{3}$$

$$LE = C_E \cdot \lambda \cdot \rho_a \cdot u_z \cdot (q_{sat} - q_a) \tag{4}$$

Where,

H	=	Sensible heat flux density [W/m^2]
LE	=	Latent heat flux density [W/m^2]
C_H	=	Bulk transfer coefficient for sensible heat
C_E	=	Bulk transfer coefficient for latent heat
c_p	=	Specific heat of air [J/g/°C]
λ	=	Latent heat of vaporization of water [2450 J/g at 20°C]
ρ_a	=	Density of air [g/m^3]
u_z	=	Wind speed at z height above surface [m/s]
T_s	=	Water surface temperature [°C]
T_a	=	Air temperature [°C]
q_{sat}	=	Saturated specific humidity at water-surface temperature [kg/kg]
q_a	=	Specific humidity [kg/kg]

In near neutral atmospheric conditions, Kondo (1975) stated that the bulk transfer coefficients would be calculated using the following empirical formulae:

$$C_H = \frac{k^2}{ln\left(\frac{z-d}{z_{om}}\right) \cdot ln\left(\frac{z-d}{z_{oh}}\right)} \tag{5}$$

$$C_E = \frac{k^2}{ln\left(\frac{z-d}{z_{om}}\right) \cdot ln\left(\frac{z-d}{z_{oq}}\right)} \tag{6}$$

Where,

C_H	=	Bulk transfer coefficient for sensible heat
C_E	=	Bulk transfer coefficient for latent heat
k	=	von Karman's constant [0.41]
z	=	Height of wind speed measurement [m]
d	=	Zero plane displacement height [m]
z_{om}	=	Surface roughness of momentum [m]
z_{oh}	=	Surface roughness of sensible heat [m]
z_{oq}	=	Surface roughness of latent heat [m]

Kondo also proposed that C_E can be explained by C_H using the following relationship:

$$C_E = B \cdot C_H \tag{7}$$

Where, B is 1 for a wet surface and 0 (zero) for a dry surface

Therefore, $C_E \approx C_H$ over the water surface when the heights of sensible and latent heat are the same. Specific heat capacity of moist air is calculated using the empirical equation presented by Jensen et al. (1990), referencing Brutsaert (1982) as a function of specific humidity:

$$c_p = c_{pd} \cdot (1 + 0.84 \cdot q) \tag{8}$$

Where,

C_p = *Heat capacity of air at constant pressure [J/g/°C]*
c_{pd} = *Specific heat of dry air [1.005 J/g/°C]*
q = *Specific humidity of air [kg/kg]*

Expressing bulk transfer coefficient for sensible heat (Jensen et al., 1989; Allen and Tasumi, 2005):

$$C_H = \frac{1}{u_z \cdot r_h} \tag{9}$$

Where, r_h is the aerodynamic resistance for heat transfer between the surface and elevation z. Therefore to calculate evaporation from lake surface, a relationship was developed between water surface temperature, Ts at the time of satellite overpass and temperature gradient, dT:

$$dT = T_s - T_a \tag{10}$$

Where dT is the near surface to air temperature difference ($T_s - T_a$). Assuming this relationship is linear, dT is expressed (Tasumi, 2003):

$$dT = aT_s + b \tag{11}$$

a and b coefficients. To calculate a and b, equation 3 was combined with Monin-Obukov stability function, and both equations were iteratively solved for dT, and $C_{H,}$ using H values at two points, one off-shore point where the flux was measured and another dry spot on-shore. Using the two values for H, the coefficients a and b were developed for equation 11.

Once “a” and “b” were defined, H and C_H for each pixel were calculated by combining equations 11, 3 and the Monin-Obukov function. Assuming C_H is equal to C_E, equation 11, 10 and 4 were solved to determine dT, T_a and LE for each pixel. Once LE flux (pixel x) for the time of satellite overpass was calculated, then the 24 hour evaporation values for each pixel (x) were estimated by multiplying the incident LE (x) values by the ratio of LE_{24}/LE_i at the off-shore tower.

RESULTS AND CONCLUSION

ASTER surface temperatures were available for December 22, 2001. Using the procedure described, evaporation rate was estimated for the Elephant Butte Reservoir. Figure 3a shows that there is a significant variability in the evaporation rate across the reservoir. The variability was caused by variation in water surface temperature, heat storage and probably wind velocity. In another study (in progress) flux is being measured at another point in the reservoir. This second point will be used to validate the procedure presented in the current paper. The variability of surface temperature (figure 3B) is analogous to spatial and temporal variation in reservoir evaporation.

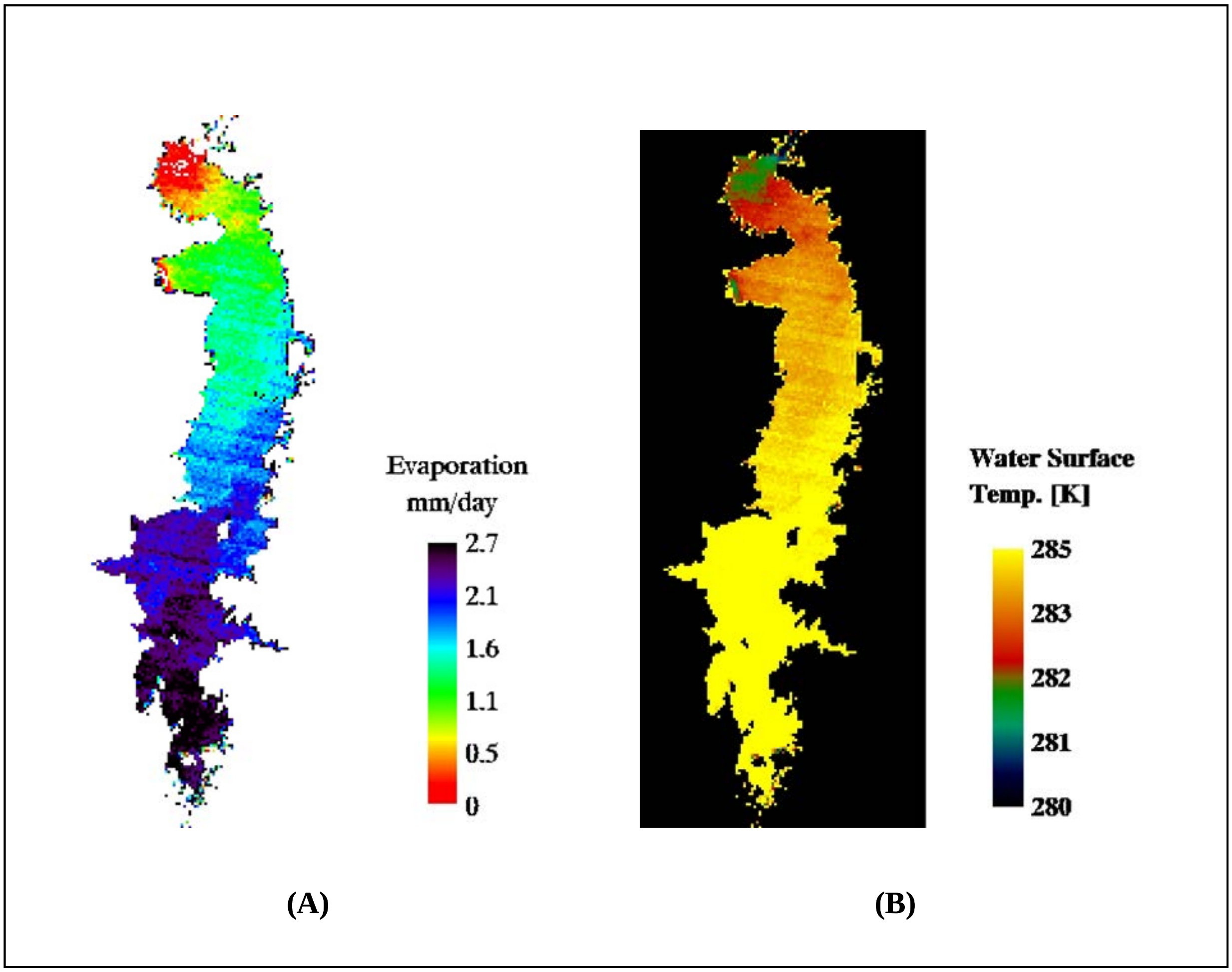


Figure 3. (A) Estimated evaporation rates and (B) surface water temperature at Elephant Butte Reservoir on December 22, 2001.

ACKNOWLEDGMENT

Our acknowledgment extends to New Mexico Office of State Engineer, United States Bureau of Reclamation, Dr. Nabil Shafike, Dr. J. Phillip King, Dr. Thomas J. Schmugge, Steven Bowser, Brent Tanzy, Christopher Almy, Jimmy Moreno, Zack Libbin, Vien Tran, and Ms. Julie Moore.

REFERENCES

Allen, R. G., and Tasumi, M. (2005). Evaporation from American Falls Reservoir in Idaho via a combination of Bowen ratio and eddy covariance. Paper presented to Proceedings 2005 EWRI Conference, Anchorage, Alaska, May 15-19.

Brutsaert, W. (1982). *Evaporation into the atmosphere: theory, history, and applications.* Dordrecht, Netherlands: D. Reidel Publ. Co.

Dingman, S. L. (2002). *Physical hydrology*. – 2nd edition. Upper Saddle River, New Jersey: Prentice-Hall., Inc.

Farnsworth, R. K., Thompson, E. S., and Peck, E. L. (1982). Evaporation atlas for the contiguous 48 United States. *NOAA Technical Report* NWS 33.

Gunaji, N. N. (1968). Evaporation investigations at Elephant Butte Reservoir in New Mexico. *Publications of the International Association d'Hydrologie Scientifique* 78: 308-325.

Harbeck, G.E., Jr. (1962). A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory. *Professional Papers of the U.S. Geological Survey* 272-E, 101-105.

Jensen, M. D., Burman, R. D., and Allen, R. G. (Eds.). (1990). *Evapotranspiration and irrigation water requirements*. ASCE Manuals and Reports on Engineering Practice no.70. New York: American Society of Civil Engineers.

Kondo, J. (1975). Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology*, 9, 1, 91-112.

Monteith, J.L. and Unsworth, M.H. (1990). *Principles of Environmental Physics,* Second Edition, Butterworth Heinemann. London. ISBN 0-7131-2931-X

Scurlock, D. (1998). From the Rio to the Sierra: an environmental history of the Middle Rio Grande Basin. *General Technical Reports of the U.S. Forest Service* RMRS-GTR-5. X, 440p.
Tasumi, M. 2003. *Progress in operational estimation of regional evapotranspiration using satellite imagery*. Ph.D. diss. Moscow, Idaho: University of Idaho. 357p.

U.S. Bureau of Reclamation. (2005). *Elephant Butte and Caballo Reservoirs' monthly elevation report for October 2005*. Retrieved October 20, 2005 from http://www.usbr.gov/uc/elpaso/water/Reservoirs/index.html

EVAPOTRANSPIRATION OF DEFICIT IRRIGATED SORGHUM AND WINTER WHEAT

T.A. Howell[1]
J.A. Tolk[2]
S.R. Evett[3]
K.S. Copeland[4]
D.A. Dusek[5]

ABSTRACT

Deficit irrigation commonly is used in regions with reduced or limited irrigation capacity to increase water use efficiency (WUE). This research measured winter wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* L. Moench) water use (ET) and yields so WUE could be determined. Two precision weighing lysimeters were used to accurately measure the crop ET from fully irrigated (FULL) fields and deficit irrigated (DI) fields. The DI wheat was an irrigation cutoff at the jointing growth stage as might be used if available irrigation water was being shifted to summer crops while the sorghum DI used a reduced irrigation rate (~50% FULL irrigation) as might occur with a lower irrigation capacity. Both crops were irrigated by a lateral-move sprinkler system at Bushland, Texas. Wheat ET was decreased by 20% from 849 to 677 mm with a 76% decline in irrigation. Sorghum ET decreased 10% from 621 mm to 560 mm with a 48% decline in irrigation. WUE of sorghum for both grain and dry matter increased slightly with DI but seed mass, and harvest index were unaffected. DI irrigated wheat extracted soil water to a depth of 1.7 m in the Pullman soil with some apparent root extraction to the 2.3-m depth. Sorghum extracted soil water mainly above 1.2 m in the Pullman soil profile if well watered, but DI sorghum extracted soil water to 1.7 m. Sprinkler DI of sorghum beginning with a nearly full soil water content profile permitted the crop to better exploit the soil profile water and minimize soil water deficit effects on crop yield in a year with typical summer rainfall for Bushland (~210 mm) such that yield was not reduced by DI. Cutting off winter wheat irrigation in early spring with a near full soil water profile at jointing, permitted the wheat crop to fully exploit the soil water reservoir when rainfall was normal.

INTRODUCTION

Deficit irrigation as characterized by English et al. (1990) has the fundamental goal to increase water use efficiency (WUE). Fereres and Soriano (2006) recently reviewed deficit irrigation (DI) and concluded that the level of the DI supply should be 60-100% of full evapotranspiration (ET) needs in most cases to improve water productivity. They indicated “regulated deficit irrigation” (RDI) was successful in several cases, especially with fruit trees and vines, to not

[1]Research Leader, USDA-ARS, P.O. Drawer 10, Bushland, TX 79012-0010; email: tahowell@cprl.ars.usda.gov.
[2]Plant Physiologist, USDA-ARS, P.O. Drawer 10, Bushland, TX 79012-0010; email: jtolk@cprl.ars.usda.gov
[3]Soil Scientist, USDA-ARS, P.O. Drawer 10, Bushland, TX 79012-0010; email: srevett@cprl.ars.usda.gov.
[4]Soil Scientist, USDA-ARS, P.O. Drawer 10, Bushland, TX 79012-0010; email: kcopeland@cprl.ars.usda.gov.
[5]Agron. (Collaborator), USDA-ARS, P.O. Drawer 10, Bushland, TX 79012-0010; email: ddusek@cprl.ars.usda.gov.

only increase water productivity but also farm profit. Deficit irrigation is widely used in the Southern High Plains and Columbia Basin in the U.S. with their limited irrigation capacities (Musick et al., 1988; English, 1990). High irrigation frequencies have been reported by Miller (1977) and Miller and Aarstad (1976) to improve DI results with sugarbeet on sandy soils, but Faci and Fereres (1980) and English and Nakamura (1989) reported little or no effect of irrigation frequency on DI with cereal crops, especially on finer texture soils. Farre and Faci (2006) reported greater WUE with sorghum (*Sorghum bicolor* L. Moench) compared with corn (*Zea mays* L.) with DI in Spain on a loam soil. Tolk and Howell (2003) reported mean WUE for sorghum of 1.46 kg m^{-3} at Bushland, Texas on the Pullman clay loam soil, but they reported a greater WUE for the Amarillo sandy loam soil and smaller WUE for the Ulysses silt loam soil. They also reported differences in WUE in two seasons across four irrigation levels.

The purpose of this paper is to present and briefly discuss and describe the ET of deficit and more fully irrigated grain sorghum and wheat measured at Bushland, Texas with precision weighing lysimeters (Marek et al., 1988; Howell et al., 1995a) and the resulting WUE (for both grain and biomass) computed from the ET and yield. The crops were produced in large fields that were sprinkler irrigated frequently (2-3 times per week if required) to maintain adequate soil water for the “well-watered” crop ET.

PROCEDURES

This study was conducted at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (35º 11' N lat.; 102º 06' W long.; 1,170 m elev. above MSL) in 1991 to 1993. Crop ET was measured with two weighing lysimeters (Marek et al., 1988) each located in the center of two 4.4-ha 210 m E-W by 210 m N-S fields. The soil at this site is classified as Pullman clay loam (fine, mixed, superactive thermic Torrertic Paleustoll) (Unger and Pringle, 1981; Taylor et al., 1963) which is described as slowly permeable because of a dense B22 horizon about 0.3 to 0.5 m below the surface. The two east lysimeter fields were used for this experiment. The plant available water holding capacity within the top 2.0 m of the profile is approximately 240 mm (Tolk and Howell, 2001) and ~200 mm to the 1.5-m depth. A calcareous layer at about the 1.4 m depth somewhat limits rooting and water extraction below this depth, depending on the crop. Variations of this soil series are common to more than 1.2 million ha of land in this region and about 1/3 of the sprinkler-irrigated area in the Texas High Plains (Musick et al., 1988). Weighing lysimeters offer one of the most accurate means to measure ET (Hatfield, 1990). Predominate wind direction is SW to SSW, and the unobstructed fetch (fallow fields or dryland cropped areas) in this direction exceeds 1 km. The field slope is less than 0.3 percent. More descriptive information on the facility is provided in Howell et al. (1995b), Howell et al. (1997), Howell et al. (1998), Howell et al. (2004), and Evett et al. (2000).

Agronomic Methods

Winter wheat (*Triticum aestivum* L.; CV TAM-107) was seeded on 27-28 September 1991 (DOY[6/] 269-270) in E-W rows 0.25-m apart with a conventional grain drill on the two east lysimeter fields. Previous crops were irrigated corn (*Zea mays* L.) in 1990 and fallow until fall 1991 (8 months). Plant density was 192 plants m^{-2}. Fertilizer rate was 11.2 g (N) m^{-2} applied on 29 August 1991 (DOY 241). The fields were uniformly irrigated on 29 September 1991 (DOY 272) with 20 mm for germination and uniform emergence. Plant emergence was on 7 October 1991 (DOY 280). The NE field had some lodging on about DOY 135 in 1992 (14 May). The SE lysimeter was hand harvested on 17 June 1992 (DOY 169) and the NE lysimeter was hand harvested on 29 June 1992 (DOY 181).

Sorghum (*Sorghum bicolor* L. Moench; CV, DK-56[7/] (Dekalb, Monsanto Co., St. Louis, Missouri), was planted in the field on 27 May 1993 (DOY 147) in E-W rows 0.76 m apart with a six-row conventional farm planter. Previous crops were fully irrigated corn in 1990, the wheat described above, and fallow from wheat harvest until sorghum planting (10 months). The six rows at each lysimeter [about 10 m total length] with four rows in the lysimeter were planted by hand with the same sorghum cultivar and later thinned to match the field plant population. The SE lysimeter was planted on May 27 (DOY 147), and the NE lysimeter was planted on 28 May (DOY 148). Irrigation (16 mm) was applied uniformly on 28 May (DOY 148) for seed germination and uniform emergence. The final mean emerged field plant stand was 22 plants m^{-2} in the two fields. Harvest plant density counts averaged 20-21 plants m^{-2} for both fields and lysimeters. The fields and lysimeters were fertilized on 8 May (DOY 159) at the rate of 11.2 g (N) m^{-2} with granular urea (45-0-0) and disked to incorporate. The lysimeter fields were cultivated and furrow diked (both to retain rain and irrigation amounts as well as match the ‘free board” water retention by the lysimeter walls). The lysimeters were hand harvested on 5-6 Oct (DOYs 278-279), and the fields were combine harvested on the same dates.

Lysimeter Measurements

Lysimeter mass was determined using a Campbell Scientific CR-7X data logger to measure and record the lysimeter load cell (Interface SM-50) signal at 0.5-Hz (2 s) frequency. The load cell signal was averaged for 5 min and later reported as 30-min means (reported on the mid point of the 30 min, i.e. data were averaged from 0-30 minutes and reported at 15 min). The lysimeter mass resolution was 0.01 mm, and its accuracy exceeded 0.05 mm (Howell et al., 1995a). Daily ET was determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation, precipitation, or dew) divided by the lysimeter area (9 m^2). A pump regulated to -10 kPa provided vacuum drainage, and the drainage effluent was held in two tanks suspended from the lysimeter (their mass was part of the total lysimeter mass) and independently weighed by load cells (drainage rate data are not reported here). ET for each 24-h period was divided by 1.02 to adjust the lysimeter area to the mid point

---

[6/] DOY – Day of Year.
[7/] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

between the two walls (10 mm air gap; 9.5 mm wall thickness; 9.18-m^2 area instead of 9.00-m^2 area). This correction would be applicable for full-cover crops, but it would not be necessary for bare soil conditions. Nevertheless, it was applied to all data uniformly.

Irrigation Treatments

Wheat: The east lysimeter fields were irrigated with a lateral-move sprinkler system with the north field (NE) and south field (SE) irrigated similarly until early spring 12 March (DOY 72) at the jointing stage when irrigations were ceased on the SE field to simulate the common deficit irrigation practice of switching irrigations to preplant irrigations for summer crops like corn or sorghum. Irrigations were applied with a 10-span lateral-move sprinkler system (Lindsay Manufacturing, Omaha, Nebraska) with an end-feed hose. The NE field and lysimeter (designated as the FULL treatment) continued to be irrigated to minimize soil water deficits to maintain non water stressed. The SE lysimeter and field were allowed to deplete the soil water reserves until harvests (DI treatment).

Sorghum: The east lysimeter field was irrigated with a lateral-move sprinkler system with the north half (NE) being irrigated to meet the crop water use (FULL treatment) and the south half (SE) being DI with approximately 50% of the FULL rate by using smaller nozzles. This simulated a reduced irrigation capacity on the SE field and lysimeter. The FULL treatment was managed to meet the water demand of the crop. The sprinkler system was aligned N-S, and irrigated E-W or W-E. The system was equipped with gooseneck fittings and spray heads (Senninger Super Spray, Orlando, Florida) with concaved spray plates on drops located about 1.5 m above the ground and 1.52 m apart. Each spray head was equipped with a 100-kPa pressure regulator and a 1-kg polyethylene drop weight. Irrigations were scheduled to meet the ET water use rate and were typically applied in one to two 25-mm applications per week. Irrigations were managed on the FULL treatment to minimize soil water deficits with the available irrigation capacity allowing 25-30 mm for rainfall storage. The DI treatment allowed the soil water profile to gradually deplete.

Soil Water Measurements

Soil water contents were measured periodically using a neutron probe (model 503DR Hydroprobe. CPN International, Inc., Martinez, California) at 0.2-m depth increments beginning with the 0.10-m depth using 60-s counts. Two access tubes were located in each lysimeter (read to 1.9 m depth) and four tubes were located in the field surrounding each lysimeter (read to 2.3-m depth). The probe was field calibrated for the Pullman soil using a method similar to that described by Evett and Steiner (1995).

Plant and Yield Sampling

Plant samples from three separate 1.5-m^2 areas were obtained periodically to measure crop development. These field samples were taken at sites about 10 to 20 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. Leaf area index (LAI), crop height (CH), and aboveground dry matter (DM) were measured from three samples. Final yield was measured by harvesting the lysimeter grain and aboveground plant matter from each lysimeter (9 m^2), and dry matter and yield at harvest were measured from three adjacent 1.5-m^2 plant samples.

Water Use Efficiency

Water use efficiency (WUE) was computed based on Viets (1962) and Zwart and Bastiaanssen (2004) [see also Farre and Faci (2006) and Tolk and Howell (2003)]. WUE_g (in kg m^{-3}) was the ratio of grain yield (dry) (GY_d; in g m^{-2}) to ET (in mm); WUE_{dm} (in kg m^{-3}) was the ratio of DM (in g m^{-2}) to ET (in mm); and harvest index (HI) was the dimensionless ratio of GY_d to DM.

RESULTS

Wheat

The crop emerged on 7 October 1991 (DOY 280). The rainfall received from crop planting until harvest was 507 mm above average for a wheat season but not greatly different from the annual precipitation at Bushland, Texas [~480-500 mm long-term annual mean]. The FULL irrigation treatment received 502 mm of seasonal irrigation and the DI treatment received 119 mm of irrigation. Measured drainage was 61 mm for the FULL treatment and 88 mm for the DI treatment. The drainage was mainly from remaining soil water following the 1990 irrigated crop, the 1990-91 winter precipitation, and the 1991 spring rainfall. Total net water applied (rain plus irrigation) was 1,009 mm for FULL and 626 mm for DI from planting and 962 mm for FULL and 582 for DI from the emergence date (Fig. 1).

Sorghum

The crop emerged on 3 June (DOY 154). The rainfall received from crop planting until harvest was 211 mm typical for a normal summer rainfall season at Bushland, Texas [~480-500 mm long-term annual mean]. Almost one-third of the growing season rain (70 mm) was received on 14 and 15 July (DOYs 195 and 196). The FULL irrigation treatment received 369 mm of season irrigation and the DI treatment received 171 mm of irrigation. Measured drainage was 46 mm for the FULL treatment and 29 mm for the DI treatment. Total net water applied (rain plus irrigation) was 586 mm for FULL and 388 mm for DI from planting and 563 mm for FULL and 365 for DI from the emergence date (Fig. 2).

Crop Evapotranspiration

The seasonal ET rates are shown in Fig. 3 for the winter wheat, and the cumulative seasonal ET was shown in Fig. 1 for comparison with the rainfall and applied water. The FULL ET [ET_{FULL}] was 849 mm and the DI ET [ET_{DI}] was 677 mm (Fig. 1; Table 1) from emergence. The wheat daily ET deficit ratio [$ET_{DI}\ ET_{FULL}^{-1}$; Fig. 3] was somewhat erratic during the early season due to the usually smaller ET rates, except following rain or irrigation when the deficit ET ratio was near 1.0 then declined after heading (DOY 118, DAE[8/] 203, 28 April) to 0.3-0.4 at physical maturity for the DI treatment (DOY 161, DAE, 245, 9 June). Wheat daily ET rates were

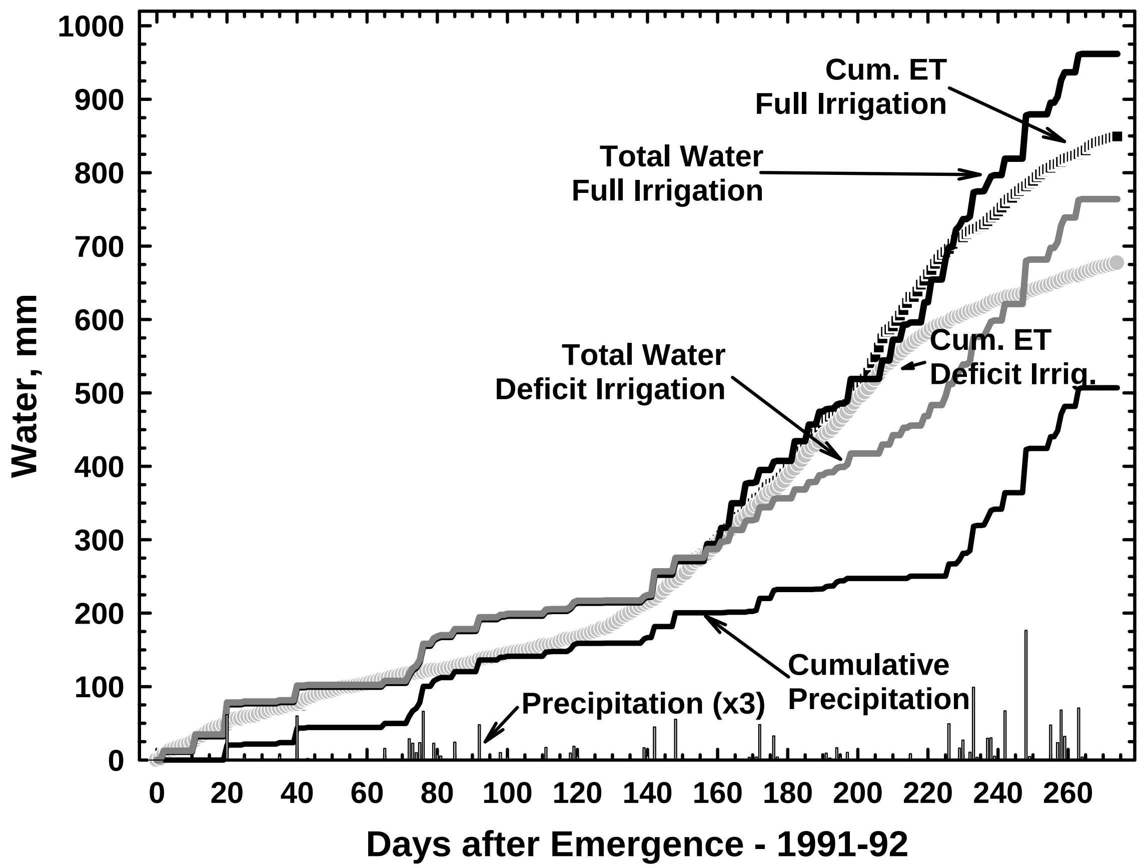


Figure 1. Water balance parameters for the 1991-92 winter wheat growing season (note the rainfall bars were multiplied by 3 to be more visible on the scale).

maximum near heading at 8-9 mm d^{-1} with three days having maximum daily ET rates from 12 to 13 mm d^{-1} under strong regional advection (Fig. 3).

Sorghum seasonal ET amounts were 621 and 560 mm for the FULL and DI treatments from emergence (Fig. 2). The sorghum FULL ET (ET_{FULL}] was about 40 mm less than that reported by Tolk and Howell (2003) for their 100% ET treatment in 1998 and 85 mm more than their reported 100% ET in 1999. It was about 30 mm less than the 100% ET treatment in 1995 for sorghum in Spain (Farre and Faci, 2006). The DI sorghum ET [ET_{DI}] was about 20 mm more than that reported by Tolk and Howell (2003) for their 50% ET treatment in 1998 and 100 mm more than their reported 100% ET in 1999. The Bushland sorghum ET_{DI} was about mid way between the T-1 ET (588 mm) and T-2 ET (544 mm) reported by Farre and Faci (2006) for 1995 in Spain from a line source experiment. The sorghum daily ET deficit ratio [$ET_{DI}\ ET_{FULL}^{-1}$;

[8/] DAE – Days after emergence.

Fig. 4] was somewhat erratic during the early season due to the usually smaller ET rates, except following rain or irrigation when the deficit ET ratio was near 1.0. Following full crop development, the sorghum deficit ET ratio gradually declined below 1.0 likely due to less soil water evaporation from the smaller irrigations until the soil water profile gradually depleted

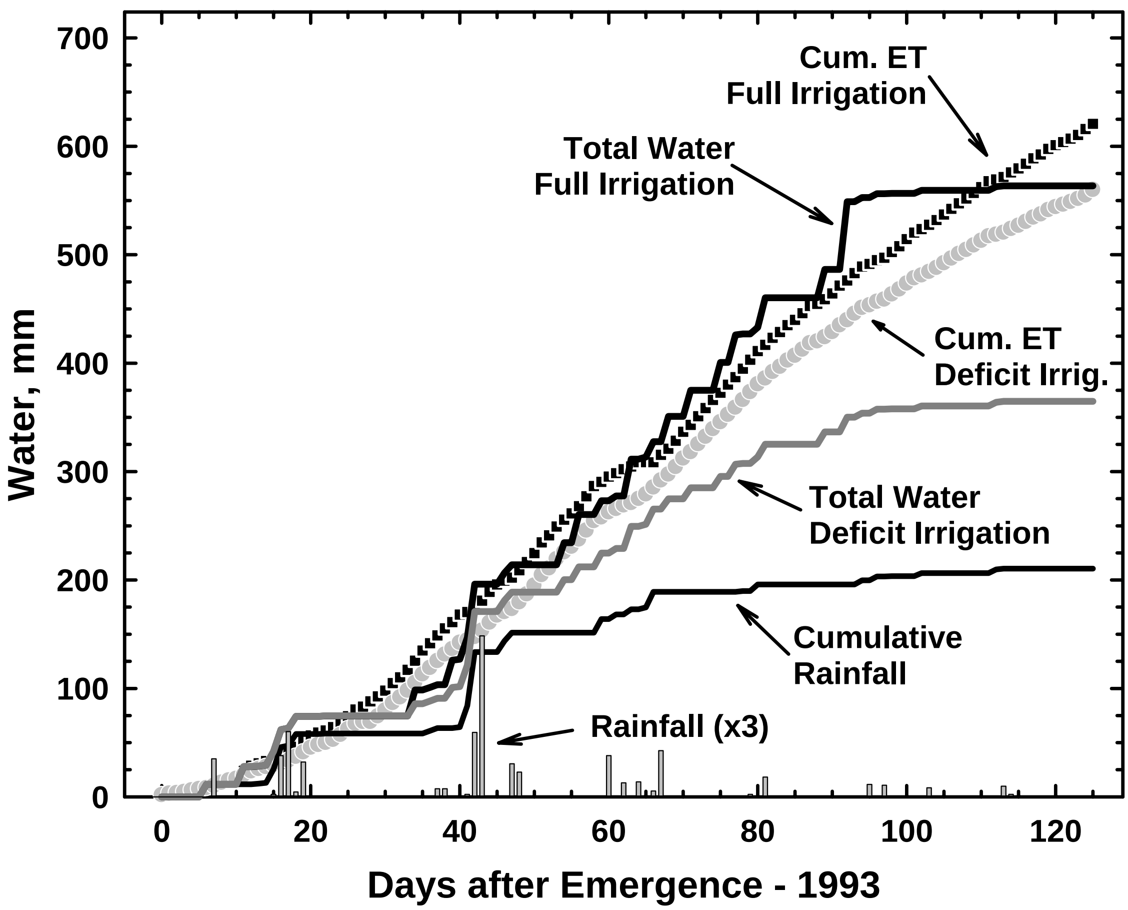


Figure 2. Water balance parameters for the 1993 sorghum growing season (note the rainfall bars were multiplied by 3 to be more visible on the scale).

further. The deficit ET ratio never was less than 0.75 after full cover until near crop maturity. Daily sorghum ET rates were about 7-8 mm d^{-1} with full cover [after the boot growth stage at ~60 DAE] with a few days with ET rates of 8-10 mm d^{-1} (Fig. 4) likely due to stronger regional advection.

Crop Development

Figure 5 shows the wheat crop development in 1991-92, and Fig. 6 shows sorghum crop development in 1993. The wheat crop height (CH) was similar for both the FULL and DI treatments until heading (DOY 118, DAE 203; Fig. 5A). The taller FULL wheat did lodge on the lysimeter following early grain development affecting the resulting lysimeter grain yields and crop ET to an unknown extent. The wheat LAI was similar until the irrigation was ceased for DI (DAE 200, DOY 95; Fig. 5B) at jointing indicating the sensitivity in leaf area development to soil water deficits; and dry matter was similar for FULL and DI irrigated wheat until boot (DAE 190, DOY 105; Fig. 5C).

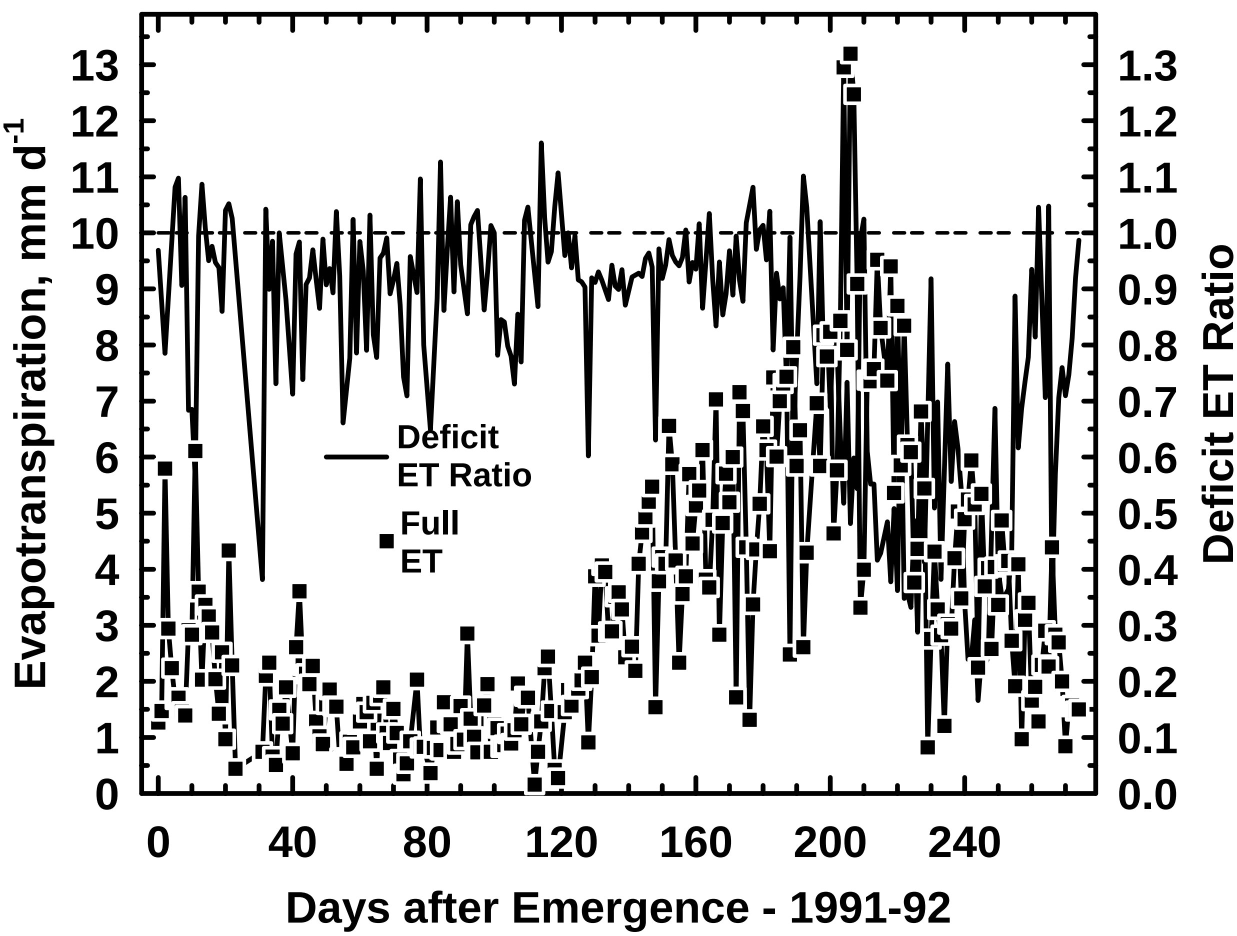


Figure 3. Daily ET rates and the daily deficit ET ratio [$ET_{DI}\ ET_{FULL}^{-1}$] (right axis scale) for the 1991-92 winter wheat.

Neither crop height (CH) nor dry matter (DM) were different (based on the standard deviations of the sample observations) between the FULL and DI sorghum treatments (Fig. 6A, 6C). Leaf area index (LAI) was essentially the same for the FULL and DI fields until about 90 DAE when the soil water profile had greater depletion (Fig. 8B). Sorghum LAI peaked near 5.0-5.2 $m^2\ m^{-2}$, which was less than the sorghum maximum of the T-1 treatment LAI (100% ET; Farre and Faci, 2006) of 6.4 $m^2\ m^{-2}$ in Spain. Maximum sorghum DM was near 1,800-2,000 g m^{-2} which was similar to that reported by Farre and Faci (2006) [dry matter of 1,838 g m^{-2}] in Spain for their T-1 treatment (100 % ET).

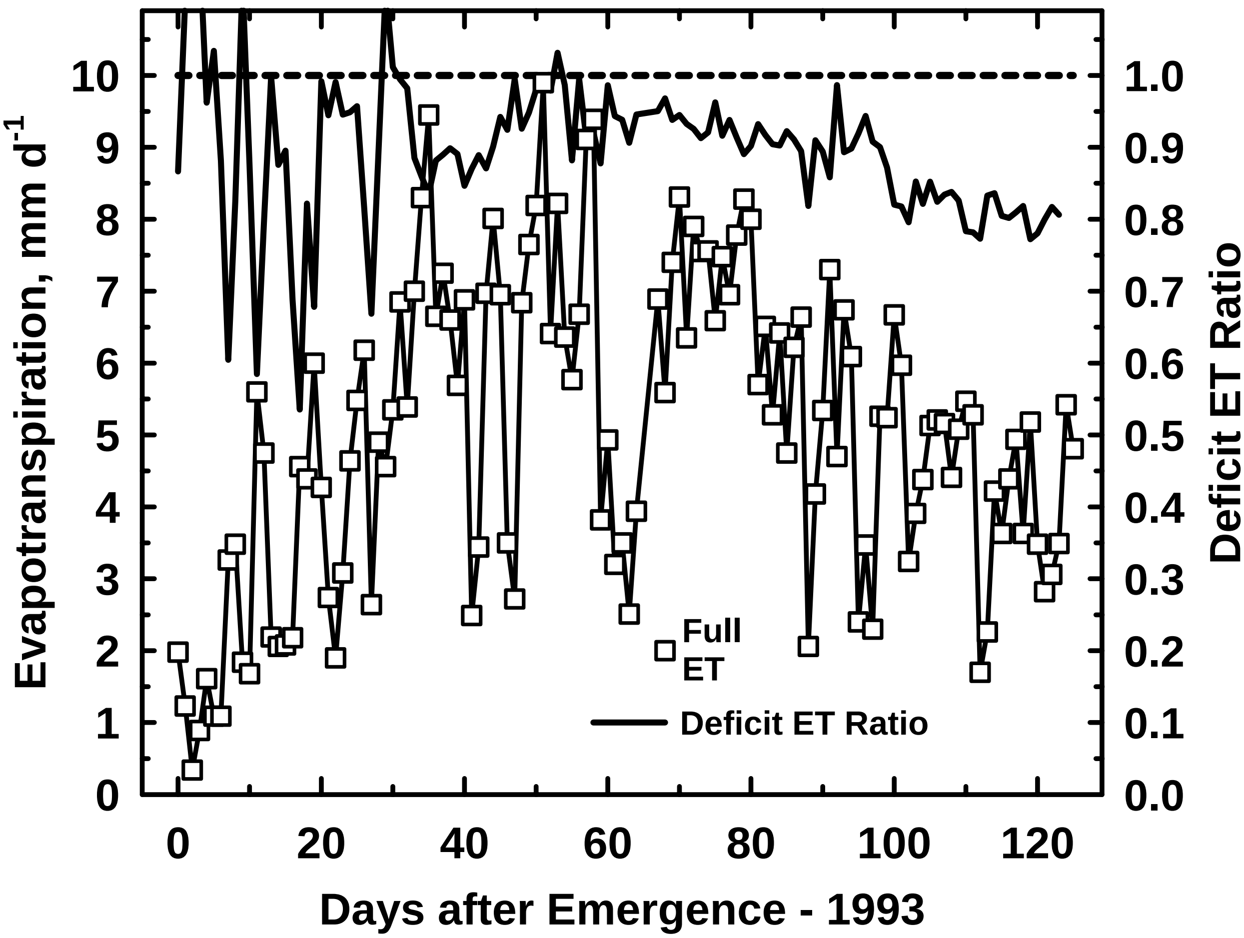


Figure 4. Daily ET rates and the daily deficit ET ratio [ET_{DI} ET_{FULL}^{-1}] (right axis scale) for the 1993 sorghum.

Soil Water

Figure 7 shows the mean field soil water content profiles for the two wheat fields, and Fig. 8 shows the mean field soil water content profiles for the two sorghum fields. Fig. 7A shows wheat soil water extraction to the 1.2-m depth prior to jointing (DAE 176, DOY 91) and minimal root extraction from the caliche layer at 1.2-1.7-m depths. After heading, the DI wheat extracted a significant amount of soil water to the 1.7-m depth with apparent root uptake by wheat in the Pullman soil to the 2.3-m depth (Fig. 7B).

The sorghum lysimeter and field soil water profiles did not differ significantly, except the lysimeters only permitted measuring to the 1.9-m depth (data not given here). Most sorghum root extraction in the Pullman soil occurred above the 1.2-m depth for the FULL field and the DI field before boot (Fig. 8 A and B), but DI sorghum extracted some soil water to the 1.7-m depth

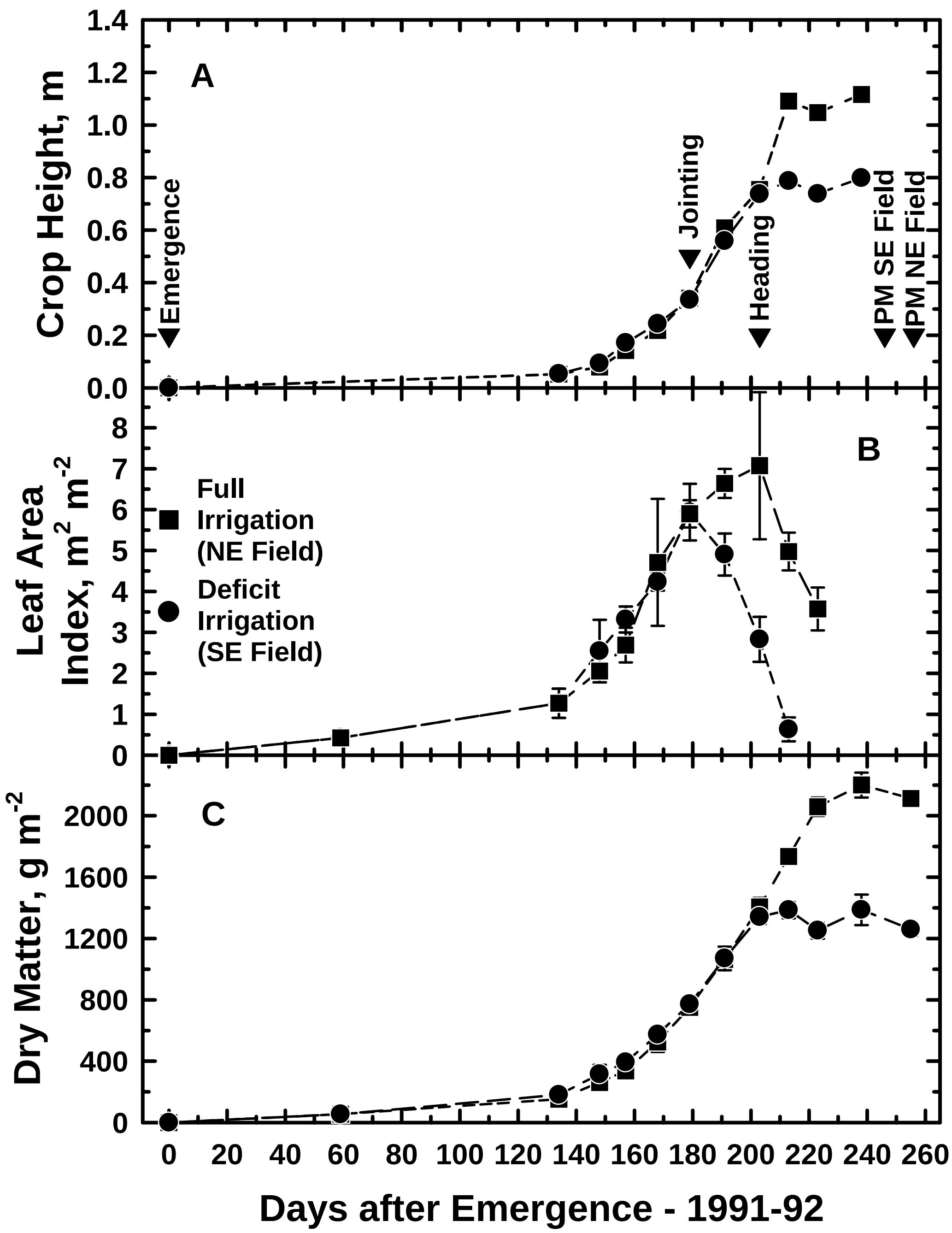


Figure 5. Crop development for 1991-92 winter wheat. Top (A) is crop height; middle (B) is leaf area index; and bottom (C) is dry matter. PM is physical maturity.

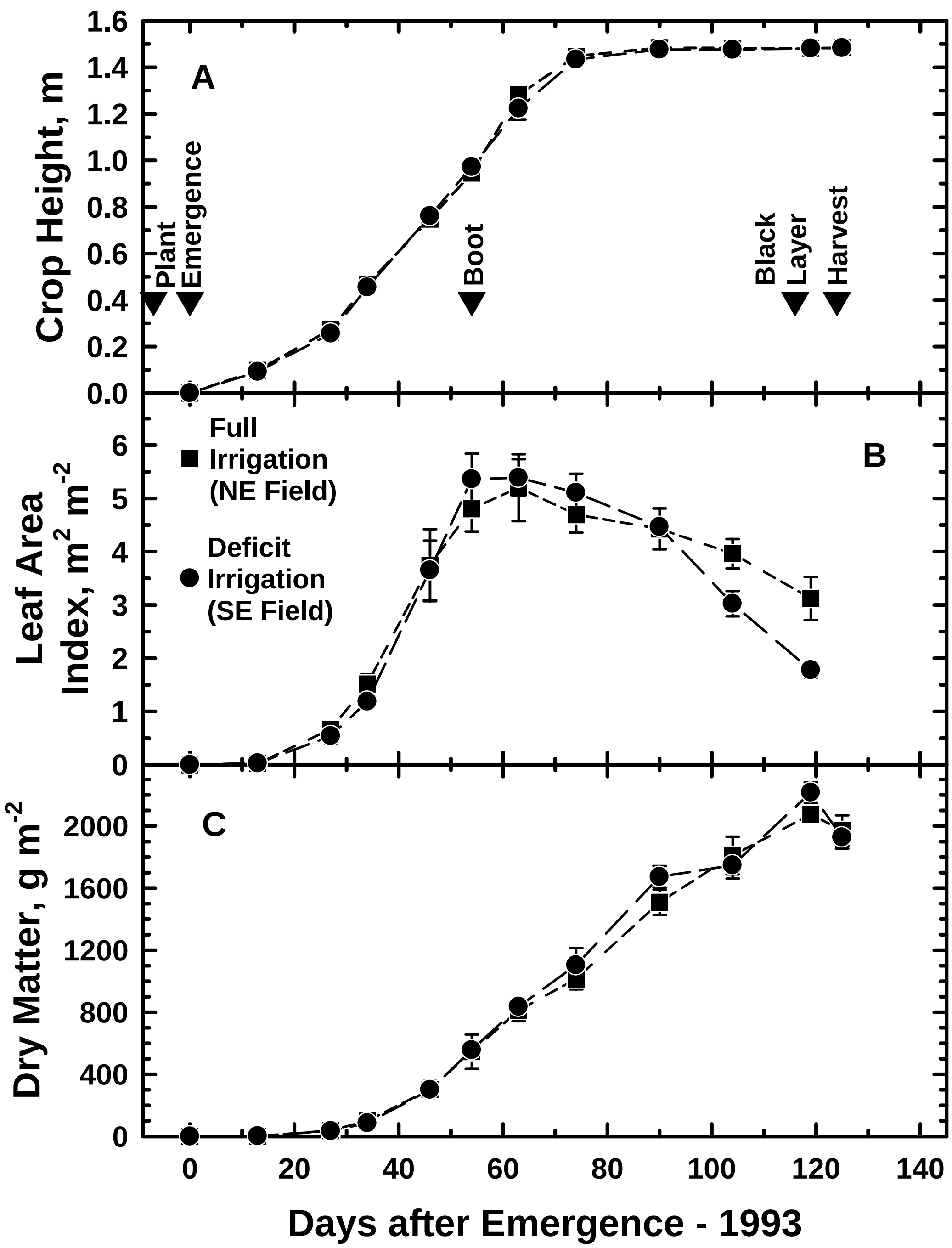


Figure 6. Crop development for 1993 sorghum. Top (A) is crop height; middle (B) is leaf area index; and bottom (C) is dry matter.

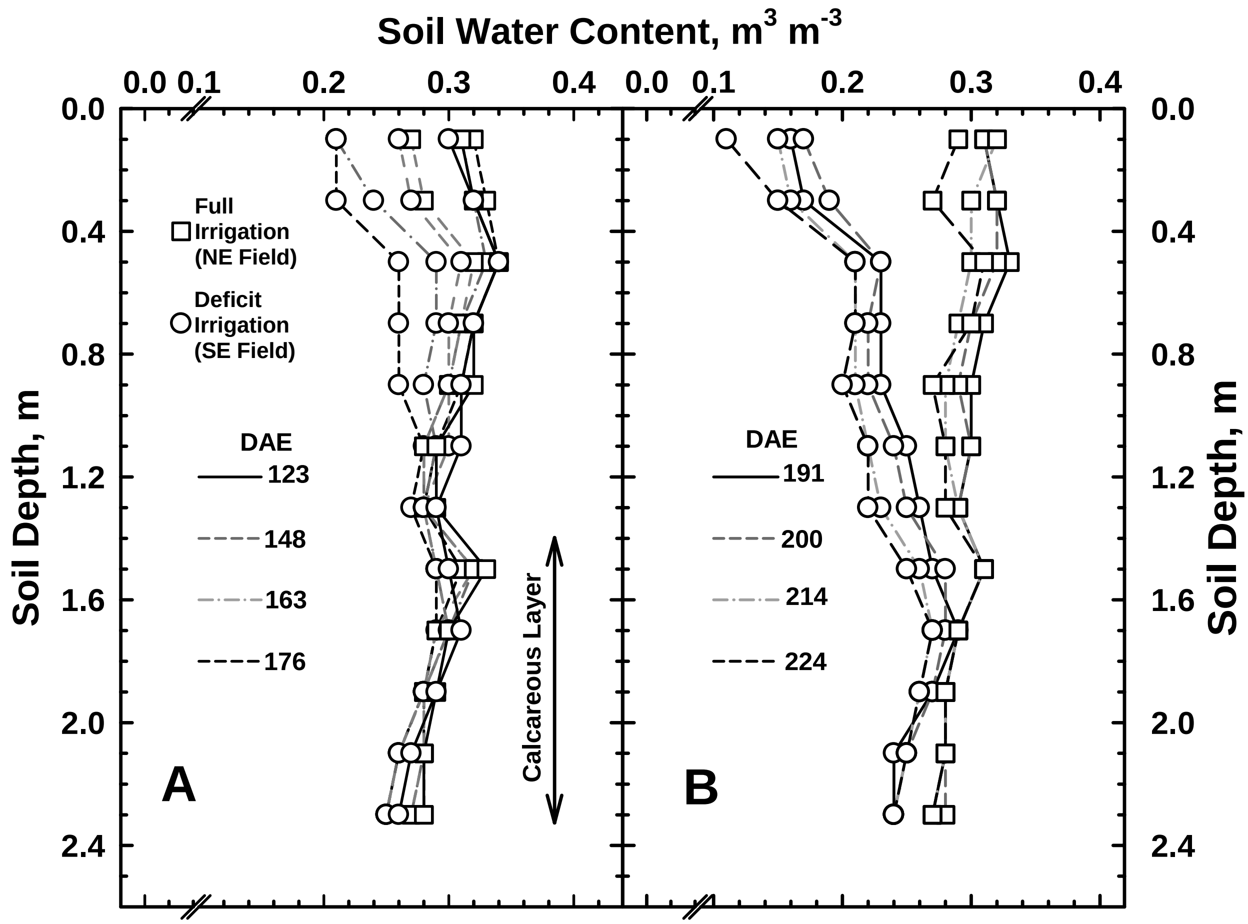


Figure 7. Soil water content profiles (mean of four neutron tube sites) in each treatment field in 1991-92 for winter wheat for emergence to joint (A) and joint to maturity (B).

in the Pullman soil after the boot stage well below the interface with the calcic horizon, showing that sorghum roots will penetrate the calcareous soil if water is available there and if overlying horizons become dry.

Water Use Efficiency

Table 1 summarizes the WUE and yield data for the wheat, and Table 2 summarizes the WUE and yield data for the sorghum. Since the SE lysimeter stems weren't harvested for a follow-up experiment on residue effects on soil water evaporation a complete analysis isn't possible, here. The NE lodging apparently affected the lysimeter yields, especially for the NE lysimeter (FULL treatment). The NE (FULL treatment) field had a DM yield of 2,113±42 g m^{-2}; grain yield of 669±48 g m^{-2}; a HI of 0.32±0.03; and a grain mass of 29.7±0.3 mg $seed^{-1}$. The SE (DI treatment) field had a dry matter yield of 1,258±48 g m^{-2}; grain yield of 373±34 g m^{-2}; a HI of 0.296±0.017; and a grain mass of 24±2 mg $seed^{-1}$. The lysimeter wheat yields were similar to regional wheat

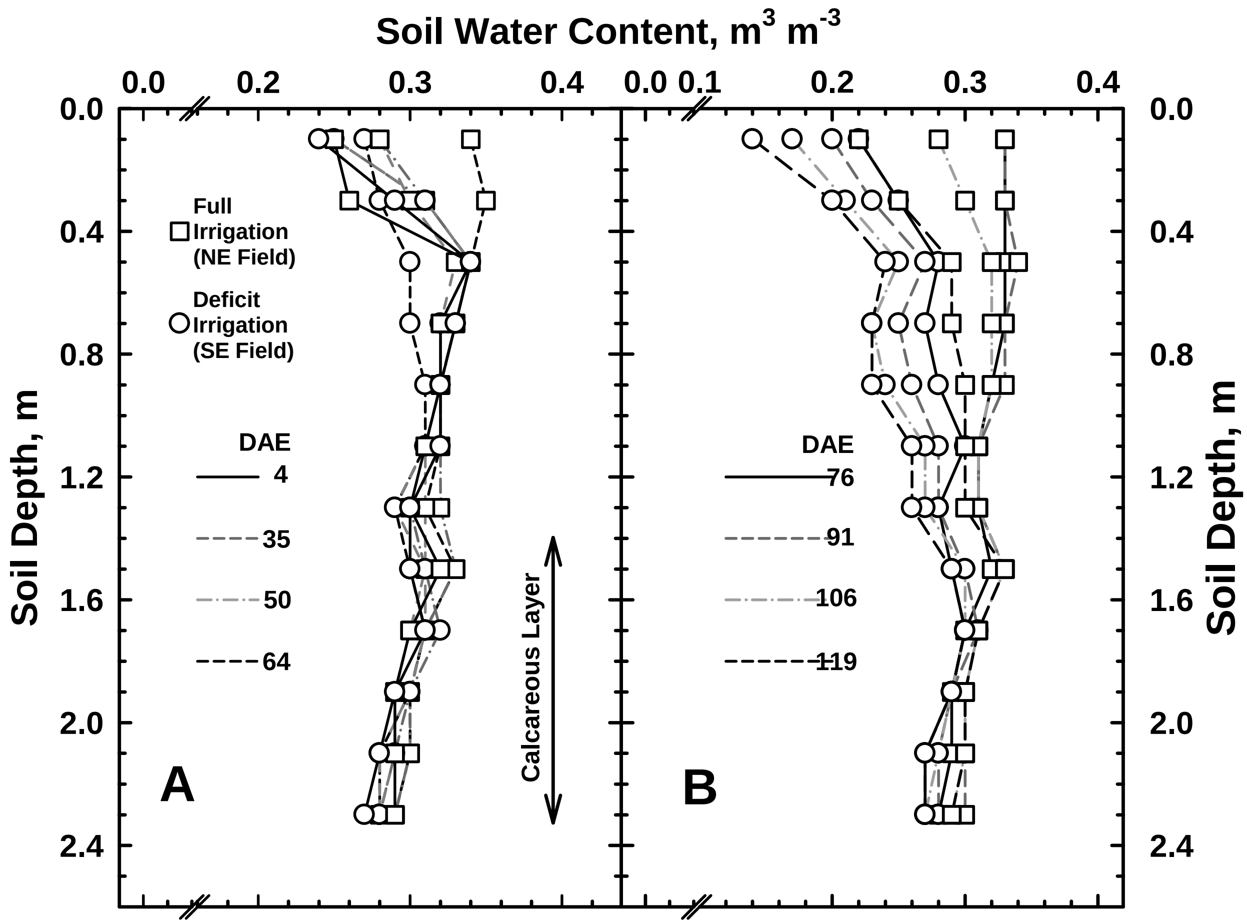


Figure 8. Soil water content profiles (mean of four neutron tube sites) in each treatment field for 1993 sorghum for emergence to boot (A) and boot to maturity (B).

yields, but affected by the lodging on the FULL lysimeter. The field yield samples are more similar to other experiment plot yields, although both the lysimeter and field HI values seemed somewhat lower than might be expected. The wheat WUE_g was 0.38 kg m^{-3} for the FULL treatment and 0.61 kg m^{-3} for the DI treatment.

The sorghum DM, grain yield, HI, and seed mass were not statistically different on the two lysimeters between the FULL and DI treatments based on a t-Test. Seed mass averaged 25 mg $seed^{-1}$, and HI averaged 0.45. The HI was somewhat lower than that reported for the T-1 treatment (100% ET) by Farre and Faci (2006) of 0.49. Mastrorilli et al. (1995) reported well-watered sorghum seed mass of 26 mg $seed^{-1}$ in Italy. Grain yield of the FULL lysimeter (898 g m^{-2}) was slightly greater than the yield reported for the T-1 treatment (100% ET) by Farre and Faci (2006) of 854 g m^{-2} in Spain or the 100% ET treatment yield reported by Tolk and Howell (2003) for the Pullman soil at Bushland of 865 g m^{-2} in 1998 and 879 g m^{-2} in 1999. Mastrorilli et al. (1995) reported well watered sorghum yield of 634 g m^{-2} in Italy in 1991.

Table 1. Summary of ET, yield, and WUE data for the winter wheat treatments in 1991-92. Numbers in parenthesis are standard deviations of the individual row (12) yields in a lysimeter.

Category	Treatments	
	FULL	DI
ET (mm)	849	677
Grain Yield (g m^{-2}) (dry)	326** (37)	412** (54)
Dry Matter (g m^{-2})	1,317 (160)	na¶
Seed Mass (mg $seed^{-1}$)	23.5* (1.4)	24.2* (0.9)
HI	0.248 (0.021)	na
WUE_g (kg m^{-3})	0.38	0.61
WUE_{dm} (kg m^{-3})	1.55	na

** Significant difference (P<0.05)
¶ The DI field residue wasn't harvested for a fallow evaporation experiment in 1992-93.
* n.s. Difference by t Test for Differences between FULL and DI.

Harvest DM of 2006 g m^{-2} at Bushland was greater than that reported for the T-1 treatment (100% ET) by Farre and Faci (2006) of 1,838 g m^{-2} in Spain. Mastrorilli et al. (1995) reported sorghum DM of 2,040 g m^{-2} in Italy for non-stressed sorghum. WUE_{dm} at Bushland was 3.23 kg m^{-3} for FULL and 3.65 kg m^{-3} for DI. Farre and Faci (2006) did not report WUE_{dm}, but their data for the T-1 treatment (100% ET) were used to compute WUE_{dm} as 3.12 kg m^{-3}. Mastrorilli et al. (1995) reported WUE_{dm} of 4.85 kg m^{-3}. WUE_g was 1.45 kg m^{-3} for the FULL lysimeter and 1.64 kg m^{-3} for the DI lysimeter. Tolk and Howell (2003) reported WUE_g that varied from 1.31 kg m^{-3} in 1998 to 1.64 kg m^{-3} in 1999 for WUE_g of 1.46 kg m^{-3} for their T-1 treatment (100 % ET). WUE_g was reported as 1.51 kg m^{-3} for non-stressed sorghum in Italy (Mastrorilli et al.,1995). WUE_g increased at 50% ET in both years on the Pullman soil as reported by Tolk and Howell (2003) but decreased with greater ET deficits in Spain (Farre and Faci, 2006).

Table 2. Summary of ET, yield, and WUE data for the 1993 sorghum treatments. Numbers in parenthesis are standard deviations of the individual row (4) yields in a lysimeter.

Category	Treatments	
	FULL	DI
ET (mm)	621	560
Grain Yield (g m^{-2}) (dry)	898* (43)	919* (45)
Dry Matter (g m^{-2})	2,006* (77)	2,042* (91)
Seed Mass (mg $seed^{-1}$)	24.9* (1.0)	24.6* (0.5)
Harvest Index (HI)	0.448* (0.018)	0.450* (0.005)
WUE_g (kg m^{-3})	1.45	1.64
WUE_{dm} (kg m^{-3})	3.23	3.65
* n.s. Difference by t Test for Differences between FULL and DI.		

CONCLUSIONS

Deficit irrigation of wheat with typical precipitation had greater yields on the lysimeters but not based on field sampling likely due to the lodging that occurred with the FULL treatment. Deficit irrigation of sorghum at Bushland in a year with typical summer rainfall did not reduce yield but increased water use efficiency. Sorghum is widely known as a drought tolerant crop (Krieg and Lascano, 1990; Farre and Faci, 2006; Tolk and Howell, 20003; Mastrorilli et al., 1995; etc.) so planned water deficits (Lamm et al., 1994) can be an effective irrigation management strategy to reduce irrigation applications, especially with lower capacity center pivot sprinkler systems. DI does impose greater risk of reduced yields from water deficits when rainfall deficits are greater than occurred here or when irrigation capacity is reduced more than 50% of that required for non-stressed production largely in agreement with the conclusion of Fereres and Soriano (2006).

ACKNOWLEDGEMENTS

These data were obtained through the dedicated and meticulous work of numerous technicians in the USDA-ARS Soil and Water Research Unit at Bushland, tEXAS. Their tireless efforts were required to obtain these data, and we sincerely recognize their dedication.

REFERENCES

English, M.J. (1990). “Deficit irrigation: Observations in the Columbia Basin.” *J. of Irrig. and Drain. Engr.* 116(3):413-426.

English, M.J., and Nakamura, B.C. (1989). "Effects of deficit irrigation and irrigation frequency on wheat yields." *J. of Irrig. and Drain.Div.* 115(IR2):172-184.

English, M.J., Musick, J.T., and Murty, V.V.N. (1990). "Deficit irrigation." pp. 631-663. In: G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.) *Management of Farm Irrigation Systems*, ASAE Mono., Am. Soc Agric. and Biol. Engr., St. Joseph, MI.

Evett, S.R., Howell, T.A., Todd, R.W., Schneider, A.D., and Tolk, J.A. (2000). "Alfalfa reference ET measurement and prediction." pp. 266-272. In: R.G. Evans, B.L. Benham, and T.P. Trooien (eds.) Proceedings of the 4th Decennial National Irrigation Symposium, Nov. 14-16, Phoenix, AZ, Am. Soc. Agric. and Biol. Engr., St. Joseph, MI.

Evett, S.R., and Steiner, J. L. (1995). "Precision of neutron scattering and capacitance type soil water content gauges from field calibrations." Soil Sci. Soc. Am. J. 59(4):961-968.

Faci, J.M., and E. Fereres, E. (1980). "Responses of grain sorghum to variable water supply under two irrigation frequencies." *Irrig. Sci.* 1:149 – 159.

Farre, I., and Faci, J.M. (2006). "Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment." *Agric. Water Mgmt.* 83:135-143.

Fereres, E. and Soriano, M.A. (2006). "Deficit irrigation for reducing agricultural water use." *J. Exp. Botany* JXB Advance Access published on November 6, 2006, DOI 10.1093/jxb/erl165.

Hatfield, J.L. (1990). "Methods of estimating evapotranspiration." pp. 435-474. In: B.A. Stewart and D.R. Nielsen (eds.) *Irrigation of Agricultural Crops*, Agron. Mono. No 30, Am. Soc. Agron., Madison, WI.

Howell, T.A., Evett, S.R., Tolk, J.A., and Schneider, A.D. (2004). "Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the Northern Texas High Plains." *J. Irrig. and Drain. Engr. (ASCE)* 130(4):277-285.

Howell, T.A., Schneider, A.D., Dusek, D.A., Marek, T.H., and Steiner, J.L. (1995a). "Calibration and scale performance of Bushland weighing lysimeters." *Trans. ASAE* 38(4):1019-1024.

Howell, T. A., Steiner, J.L., Schneider, A.D., Evett, S.R., and Tolk, J.A. (1997). "Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn - Southern High Plains." *Trans. ASAE* 40(3)623-634.

Howell, T.A., Steiner, J.L., Schneider, A.D., and Evett, S.R. (1995b). "Evapotranspiration of irrigated winter wheat — Southern High Plains." *Trans. ASAE* 38(3):745-759.

Howell, T.A., Tolk, J.A., Schneider, A.D., and Evett, S.R. (1998). Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity.” *Agron. J.* 90(1):3-9.

Krieg, D.R., and Lascano, R.J. (1990). “Sorghum.” pp. 719–740. In: Stewart, B.A.,Nielsen, D.R. (eds.), *Irrigation of Agricultural Crops*. Am. Soc. of Agron., Madison, WI.

Lamm, F.R., Rogers, D.H., and Manges, H.L. (1994). “Irrigation scheduling with planned soil water depletion.” *Trans. ASAE* 37:1491–1497.

Marek, T.H., Schneider, A.D., Howell, T.A., and Ebeling, L.L. (1988). “Design and construction of large weighing monolithic lysimeters.” *Trans. ASAE* 31(2):477-484.

Mastrorilli, M., Katerji, N., and Rana, G. (1995). “Water efficiency and stress on grain sorghum at different reproductive stages.” Agric. Water Mgmt. 28:23–24.

`Miller, D.E. (1977). “Deficit high-frequency irrigation of sugarbeets, wheat, and beans.” pp. 269-282. In: Proc. Specialty Conference on Water Irrigation and Management for Drainage, ASCE, Reno, NV, 20-22 July 1977.

Miller, D.E., and Aarstad, J.S. (1976). “Yields and sugar content of sugar beets as affected by deficit high-frequency irrigation.” *Agron. J.* 68:231-234.

Musick, J.T., Pringle, F.B., and Walker, J.D. (1988). “Sprinkler and furrow irrigation trends - Texas High Plains.” *Appl. Engr. Agric*. 4(1):46-52.

Taylor, H.M., Van Doren, C.E., Godfrey, C.L., and Coover, J.R. (1963). “Soils of the southwestern Great Plains field station.” Misc. Publ.- MP-669, Texas Agric. Exp. Stat., College Station.

Tolk, J.A., and Howell, T.A. (2001). “Measured and simulated evapotranspiration of grain sorghum grown with full and limited irrigation in three high plains soils.” *Trans. ASAE* 44(6)1553-1558.

Tolk, J.A., and Howell, T.A. (2003). “Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils.” *Agric. Water Mgmt.* 59:97–111.

Unger, P.W., and Pringle, F.B. (1981). “Pullman soil: Distribution, importance, variability, and management.” Bull. 13 - 1372, Texas Agric. Exp. Stat., College Station.

Viets, F.G. (1962). “Fertilizers and the efficient use of water.” *Adv. Agron.* 14:223-264.

Zwart, S.J., Bastiaanssen, W.G.M. (2004). “Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize.” *Agric. Water Mgmt.* 69:115–133.

EVALUATION OF A TWO-LAYER MODEL TO ESTIMATE ACTUAL EVAPOTRANSPIRATION FOR VINEYARDS

Samuel Ortega-Farias[1]*
Carlos Poblete[1]
Marcos Carrasco[1]
Albert Olioso[2]
Nadine Brisson[2]

ABSTRACT

The two-layer model of Shuttlerworth and Wallace (SW) was evaluated to estimate actual evapotranspiration (ETa) above a drip-irrigated Merlot vineyard, located in the Talca Valley, Region del Maule, Chile (35º 25' LS; 71º 32' LW ; 136m above the sea level). An automatic weather system was installed in the center of the vineyard to measure climatic variables (air temperature, relative humidity, and wind speed) and energy balance components (solar radiation, net radiation, latent heat flux, sensible heat flux, and soil heat flux) during November and December 2006. Values of ETa estimated by the SW model were tested with latent heat flux measurements obtained from an eddy-covariance system on a 30 minute time interval. Results indicated that SW model was able to predict ETa with a root mean square error (RMSE) of 0.44 mm d^{-1} and mean absolute error (MAE) of 0.36 mm d^{-1}. Furthermore, SW model predicted latent heat flux with RMSE and MAE of 32 W m^{-2} and 19W m^{-1}, respectively.

INTRODUCTION

Quantification of the actual evapotranspiration (ETa) is a key to designing strategies for improving water-use efficiency and wine quality of irrigated viticulture (Yunusa et al., 2004; Ortega-Farias et al., 2004a; and McCarthy, 1997). Evapotranspiration modeling over full canopies is common; however, little research has been done on ETa over sparse canopies such as in vineyards. ETa over vineyards is a complex function of water and energy balances of both the vine canopy and the soil surface (Heilman et al., 1994). Vineyards usually contain tall plants and widely spaced rows that produce large diurnal changes in the exposure of plants and soil to solar radiation.

Recent studies have indicated that the two-layer model of Shuttleworth and Wallace (SW) could be used to compute ETa over vineyards. In Chile, Ortega-Farias et al (2007) indicated that SW model was able to compute ETa over a drip irrigated Cabernet Sauvignon vineyard with a root mean square error (RMSE) and mean absolute error (MAE) of 0.42 mm d^{-1} and 0.36 mm d^{-1}, respectively. Sene (1994) used the SW model for estimating water consumption of a sparse vine growing under semiarid conditions in southern Spain. In this study, the parameterization of the SW model seemed sufficiently well defined so that, under dry soil conditions the only input data

[1]Research and Extension Center for Irrigation and Agroclimatology (CITRA). Universidad de Talca, Casilla 747, Talca, Chile.
[2]INRA, Climat, Sol et Environnement, Domaine Saint-Paul, Site Agroparc, 84914 Avignon, Cedex 9, France.
*M. ASCE, Corresponding author

required were direct measurements or estimates of the vine growth, solar radiation, air temperature, wind speed, and humidity above the canopy.
The objective of this study is to evaluate the two-layer model of Shuttleworth and Wallace for computing latent heat flux (LE) and actual evapotranspiration (ETa) over a drip-irrigated Merlot vineyard located in the Talca Valley, Region del Maule, Chile.

THEORY

The SW model combines a one-dimensional model of crop transpiration and a one-dimensional model of soil evaporation. Surface resistances regulate the heat and mass transfer at plant and soil surfaces, and aerodynamic resistances regulate those between the surface and the atmospheric boundary layer (Shuttlerworth and Wallace, 1985):

$$LE = C_c PM_c + C_s PM_s \tag{1}$$

where LE = latent heat flux from the canopy (W m^{-2}); PM_c and PM_s are terms (Wm^{-2}) similar to those in the Penman-Monteith model that would apply to transpiration from the canopy and evaporation from the soil, respectively; C_c and C_s are the canopy and soil surface resistance coefficients (dimensionless). Values of PMc and PMs, are obtained as follows:

$$PM_C = \frac{\Delta A + \left(\frac{\rho_a c_P D - \Delta r_a^c A_s}{r_a^a + r_a^c}\right)}{\Delta + \gamma\left(1 + \frac{\left(r_s^c\right)}{\left(r_a^a + r_a^c\right)}\right)} \quad (2) \qquad PM_S = \frac{\Delta A + \left(\frac{\rho_a c_P D - \Delta r_a^s \left(A - A_s\right)}{r_a^a + r_a^s}\right)}{\Delta + \gamma\left(1 + \frac{\left(r_s^s\right)}{\left(r_a^a + r_a^s\right)}\right)} \quad (3)$$

where Δ = slope of the saturation vapor pressure curve at the mean temperature (kPa $°C^{-1}$); A = available energy leaving the complete crop (W m^{-2}); c_p = specific heat of the air at constant pressure (1013 J kg^{-1} $°C^{-1}$); ρ_a = air density (kg m^{-3}); D = water vapor pressure deficit at the reference height (kPa); r_a^c = bulk boundary layer resistance of the vegetative elements in the canopy (s m^{-1}); A_s = available energy at the soil surface (W m^{-2}); r_a^a = aerodynamic resistance between canopy source height and reference level (s m^{-1}); γ = psychrometric constant (kPa $°C^{-1}$); r_s^c = canopy resistance (s m^{-1}); r_a^s = aerodynamic resistance between the soil and canopy source height (s m^{-1}); and r_s^s = soil resistance (s m^{-1})

A general description of aerodynamic resistances, C_s and C_c is found in Shuttleworth and Wallace (1985) and Ortega-Farias et.al (2007). The available energy at the crop canopy (A) and soil surface (As) is computed as, respectively:

$$A = Rn - G \tag{4}$$

$$As = Rn_s - G \tag{5}$$

where Rn = net radiation (Wm^{-2}); G = soil heat flux (Wm^{-2}); Rn_s = net radiation at the soil surface, which can be calculated using Beer's law as follows:

$$Rn_s = Rn \exp(-C\,LAI) \qquad (6)$$

where LAI = leaf area index ($m^2\ m^{-2}$); C = extinction coefficient of the crop for net radiation (0.5).

The surface canopy resistance, which depends on climatic factors and available soil water, is defined as the resistance to water transfer from the soil and plant to the atmosphere. The combined effect of atmospheric and soil moisture conditions on r_s^c can be expressed as follows (Ortega-Farias et al., 2004b and 2006):

$$r_s^c = \frac{\rho_a \quad C_p \quad D}{\Delta \quad (Rn - G) \quad C_F} \quad F^{-1} \qquad (7)$$

where F = normalized soil water (from 0 to 1); C_F = empirical factor (0.066). The F-value can be estimated as (Noilhan and Planton, 1989):

$$F = \frac{\theta_i - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \qquad (8)$$

where θ_{FC} = volumetric soil moisture content at field capacity (fraction); θ_{WP} = volumetric soil moisture content at wilting point (fraction); θ_i = volumetric soil moisture content in the root-zone (fraction).

MATERIALS AND METHODS

Data to evaluate LE and ETa estimated by the Shuttleworh and Wallace (SW) model were collected over a 8-year-old Merlot vineyard located in the Talca Valley, Region del Maule, Chile (35º 25' LS; 71º 32' LW; 136 m above the sea level). The climate in this area is a typical Mediterranean semiarid climate with an average daily temperature of 17.1 ^oC between September and March. Average annual rainfall in the region is between 676 mm falling mainly during the winter months. The summer period is usually dry (2.2 % of annual rainfall) and hot while the spring is on average wet (16 % of annual rainfall). The soil at the vineyard is classified as the Talca series (family Fine, mixed, thermic Ultic Haploxeralfs) with a clay loam texture. For the effective rooting depth (0-60 cm), the volumetric soil water content at field capacity (θ_{FC}) and at wilting point (θ_{WP}) were 0.32 $m^3\ m^{-3}$ (192 mm) and 0.20 $m^3\ m^{-3}$ (120 mm), respectively. Also, the total available moisture (TAM) was 0.12 $m^3\ m^{-3}$ (72 mm) at the root zone.

Merlot vines were planted in 1999 in north-south rows 2.5 m apart, with 1.5 m within-row spacing. The vines were trained in standard vertical trellis system with the main wire 0.9 m above the soil surface. The shoots were maintained in a vertical plane by three wires, the highest of which was located 1.9 m above the soil surface. This created a compact hedgerow 2.1 m high and 0.55 m wide with little foliage below the main wire. Typical vine trunk diameters were about 10.6 cm (± 1.7 cm) and soil surface was maintained free of weeds or cover crop during the experiment.

The water application was done twice a week using 4 L hr^{-1} drippers spaced at intervals of 1.5 m. To check the soil water content (θ_m) at the rooting depth, a portable TDR unit (TRASE, Soil Moisture Corp., Santa Barbara, Calif.) was used twice a week. The management allowed depletion (MAD) was 22 %, which corresponded to 40 % of TAM. The leaf area index (LAI) was measured on 552 vines using a plant canopy analyzer (LAI-2000, LI-COR, Lincold, Nebraska, USA) 2 times during the simulation period. In this case, the average LAI value for the whole vineyard was 0.76 m^2 m^{-2}

During November and December 2006, an automatic weather system was installed in the central part of the vineyard to measure energy balance components (net radiation (Rn), sensible heat flux (H), latent heat flux (LE) and soil heat flux (G)) and meteorological variables (air temperature (Ta), relative humidity (RH), wind speed (u), wind direction (w) and precipitation (Pp)). Rn was measured by a four-way net radiometer (CNR1, Kipp&Zonen Inc., Delft, Netherlands). LE was measured using an open-path infrared gas analyzer (LI-7500 IRGA; LI-COR, Inc., Lincoln, Nebraska, USA) and H was measured by a three dimensional sonic anemometer (CSAT, Campbell Sci., Logan, UT) both mounted at a height of 4.0 m (Fig.1). The minimum fetch-to-instrument-height ratio was about 200:1, sufficiently large to preclude horizontal advection. Measurements were made at 10 Hz, and means, standard deviations, and covariances were calculated for 30-min periods. Half-hour averages of all signals were recorded on an electronic datalogger (CR 5000).

Soil heat flux was estimated using eight flux plates installed 0.4 m apart on an east-west line between rows. This arrangement takes into account the effect of shade of rows during the course of the day. The flux plates of constant thermal conductivity (HFT3, Campbell Sci., Logan, UT) were placed at a 0.08 m depth. Also, two averaging thermocouple probes (TCAV, Campbell Sci., Logan, UT) were installed above each flux plate at depths of 0.02 and 0.06 m. All these sensors were sampled at 10 second intervals and the data averaged over 30 minute time-steps.

Soil evaporation was measured with microlysimeters which were made from PVC tubes of 75 mm i.d. and 150 mm in depth (Yunusa el at., 2004). Four microlysimeters were installed on either side of the vines into the inter-row and two microlysimeters were installed within the drip-line (one below drip and the other one between drippers) (Fig. 2).

Figure 1. Eddy Covariance and Weather Station

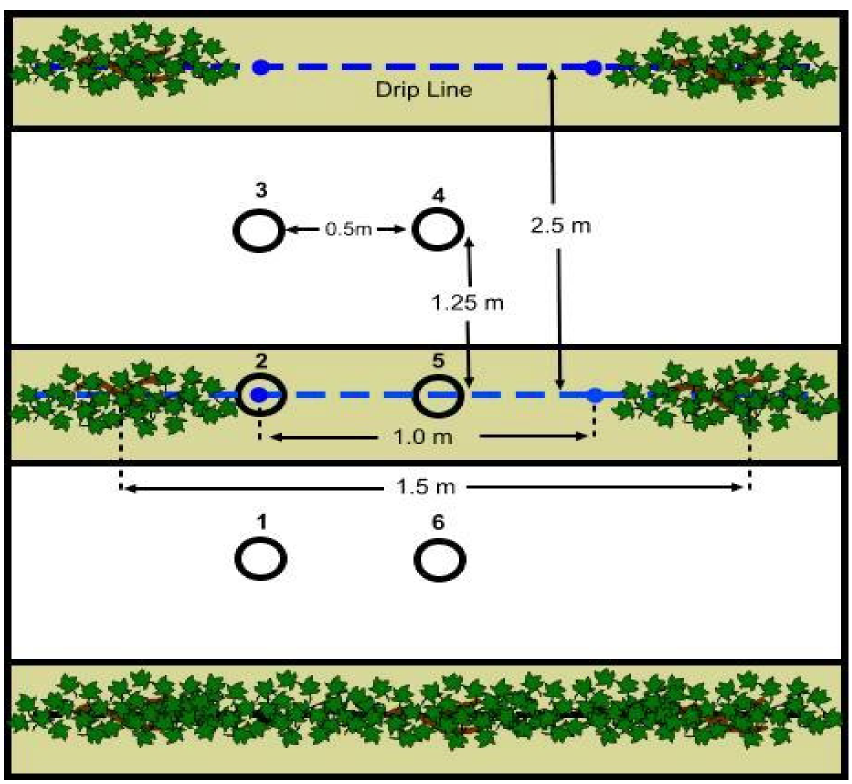


Figure 2. Schematic diagram to illustrate the distribution of microlysimeters.

In order to assess the validity of the estimation of LE, as computed from the Shuttleworth and Wallace model (LE_{sw}), our calculations were compared to latent heat flux obtained from the eddy-covariance method (LE_{ed}). Eddy covariance is the most direct micrometeorological technique for measuring turbulent fluxes (H and LE) in the surface of atmospheric boundary layer (Baldocchi et al., 1988). The eddy covariance system compute sensible heat flux (H) (W m^{-2})as the product of the volumetric heat capacity of air ($\rho_a C_p$) and the covariance between vertical wind speed and air temperature ($\overline{w'T'}$).

$$H = \rho_a C_p \overline{w'T'} \tag{9}$$

Latent heat flux (LE) (W m^{-2}) is calculated as the product of the latent heat of vaporization (L) (J g^{-1}) and the covariance between vertical wind speed and humidity ($\overline{w'\rho_v'}$).

$$LE = L\overline{w'\rho_v'} \tag{10}$$

where (w`) = instantaneous deviation of vertical wind speed from the mean (m s^{-1}); ρ_v' = instantaneous deviation of the water vapor density from the mean (g m^{-3}); ρ_a = density of air (g m^{-3}); C_p = heat capacity of air at a constant pressure (J g^{-1} K^{-1}); T' = instantaneous deviation of air temperature from the mean (K).

Also, the actual evapotranspiration was computed as a cumulative LE for the 24 hours. A regression model between LE_{sw} and LE_{ed} was performed using fluxes on a 30 minute time interval. The coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE) were all used to evaluate how well the SW model estimates matched the eddy-correlation measurements (Mayer and Butler, 1993).

RESULTS AND DISCUSSION

Figure 3 shows sensible plus latent heat flux (H+LE) from an open-path infrared gas analyzer and a 3-D sonic anemometer, respectively, versus the available energy (Rn-G) for a drip-irrigated Merlot vineyard. For the closure, values of R^2 and b were 0.97 and 0.96, respectively. Also, the slope (0.97) of the regression line was statistically different from 1.0 but the intercept (-4.0 W m^{-2}) was significantly equal to 0. Therefore, it is likely that the eddy-covariance method was providing accurate estimates of LE and H. Similar results were found by Ortega-Farias et al (2007) who indicated that the energy balance closure for a drip-irrigated Cabernet Sauvignon vineyard presented R^2 and slope values of 0.93 and 1.08, respectively. Similar results were found by Spano (2000) over a flood-irrigated Cabernet Sauvignon vineyard

Results, summarized in Table 1 and Fig. 4, indicate that there was a good agreement between LE measured by the eddy-correlation method (LE_{ed}) and that computed by the Shuttleworth and Wallace model (LE_{sw}) on a 30 minute basis. R^2 and RMSE values were equal to 0.88 and 32 W m^{-2}, respectively. Also, the statistical analysis indicated that LE_{sw} tended to be lower than LE_{ed} with a MAE value of 19 W m^{-2}. Results of the Z-test indicate that the intercept and slope were

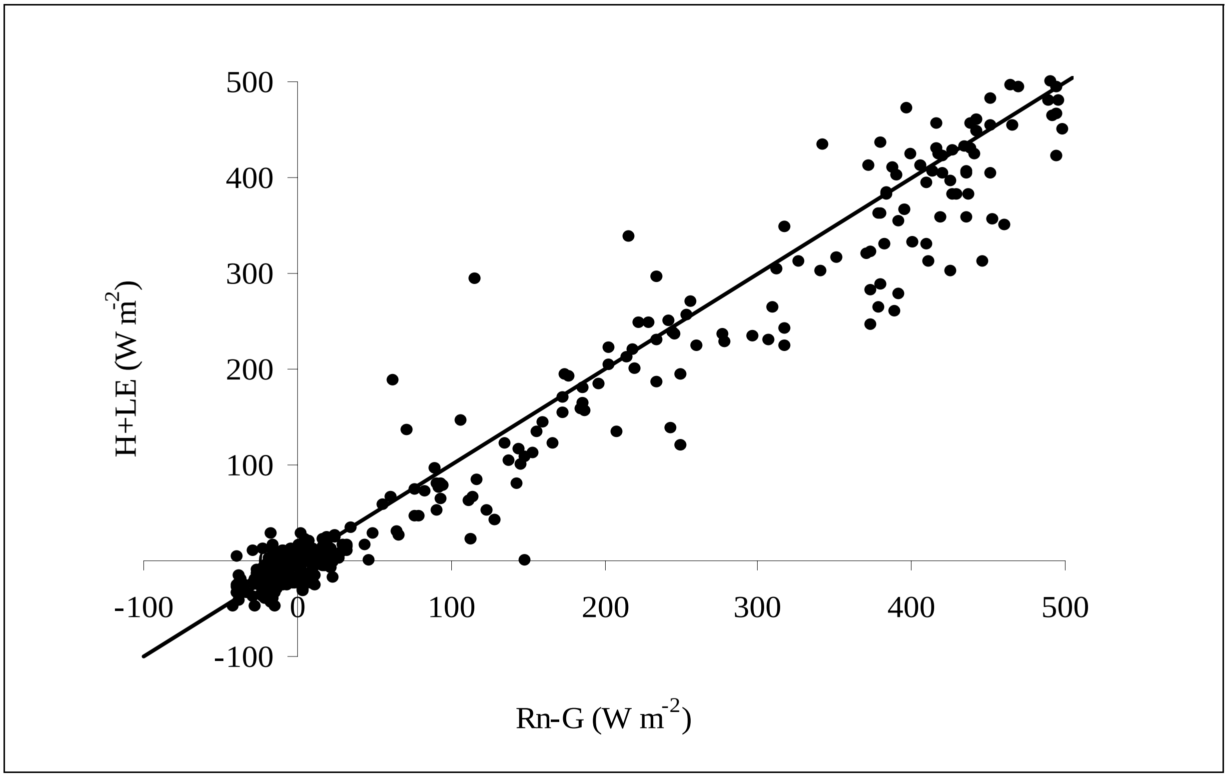


Figure 3. Sensible plus latent heat flux from eddy-covariance (H+LE) versus net radiation minus soil heat flux (Rn-G) for a drip-irrigated Merlot vineyard.

significantly different from 0 and 1.0, respectively. Comparison between both methods (Fig. 4) indicates that LE_{sw} values tended to be lower than LE_{ed} for values above 200 W m^{-2}. Furthermore, the SW model was able to simulate ETa, with R^2 and RMSE values equal to 0.61 and 0.44 mm d^{-1} (1.1 MJ m^{-2} d^{-1}), respectively (Table 1). The Z-test indicated that the intercept and slope were statistically different from 0 and 1.0, respectively. In this case, the SW model tended to underestimate ETa with a MAE value of 0.36 mm d^{-1} (0.88 MJ m^{-2} d^{-1}).

Table 1. Statistical validation of latent heat flux (LE) and actual evapotranspiration (ETa) over a drip-irrigated Merlot vineyard estimated by the Shuttleworth and Wallace model.

	RMSE	MAE	R^2	Intercept	Slope
LE	32 W m^{-2}	19 W m^{-2}	0.88	5.30 W m^{-2}	0.81
ETa	0.44 mm d^{-1}	0.36 mm d^{-1}	0.61	1.10 mm d^{-1}	0.46

RMSE = root mean square error; MAE = mean absolute error; R^2 = coefficient of determination

Daytime variation of LE_{sw} and LE_{ed} above the Merlot vineyard for a 10-day period is presented in Fig. 5. Latent heat flux increased from sunrise onwards and peaked between 15:00 and 17:00 h, then declined after that. Maximum values of LE_{sw} and LE_{ed} were between 181 and 278 W m^{-2} and between 189 and 317 W m^{-2}, respectively. The top layer of soil (0-10 cm) was dry on these days (θ_m = 0.09 m^3 m^{-3}); therefore in this instance, LE was mainly primarily represented by

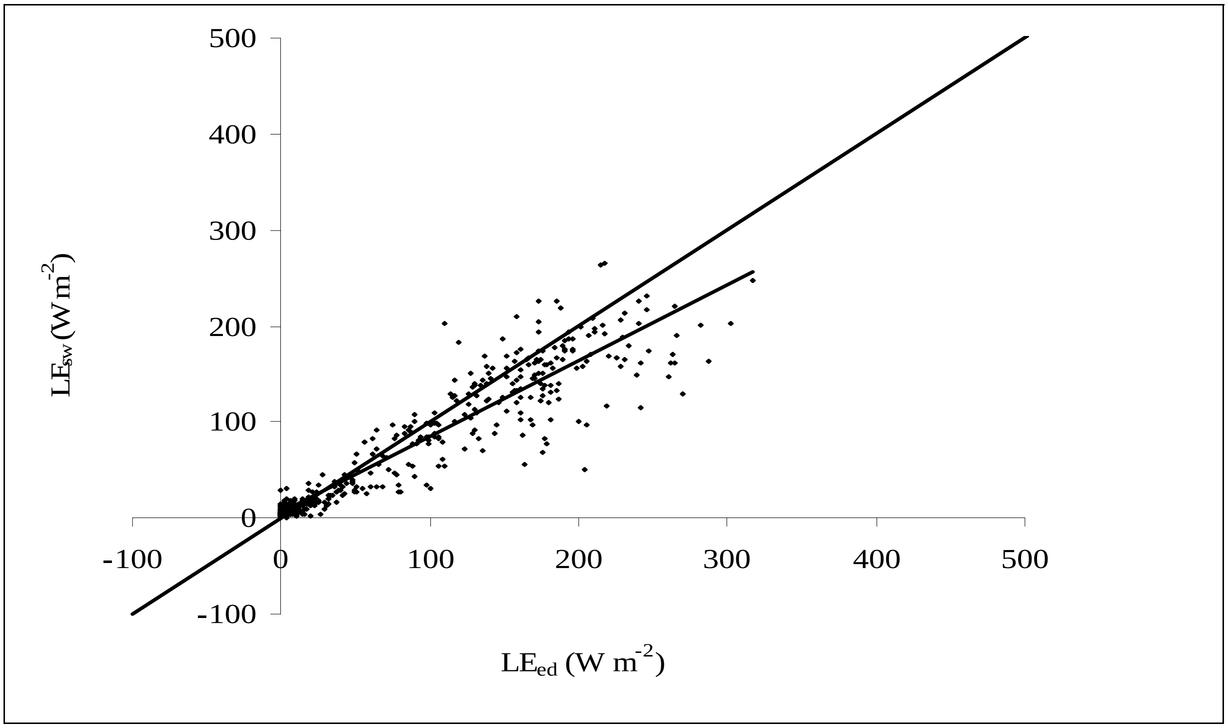


Figure 4. Comparison between latent heat flux obtained by the eddy correlation method (LE_{ed}) and computed by Shuttleworth and Wallace model (LE_{sw}) over a drip-irrigated Merlot vineyard.

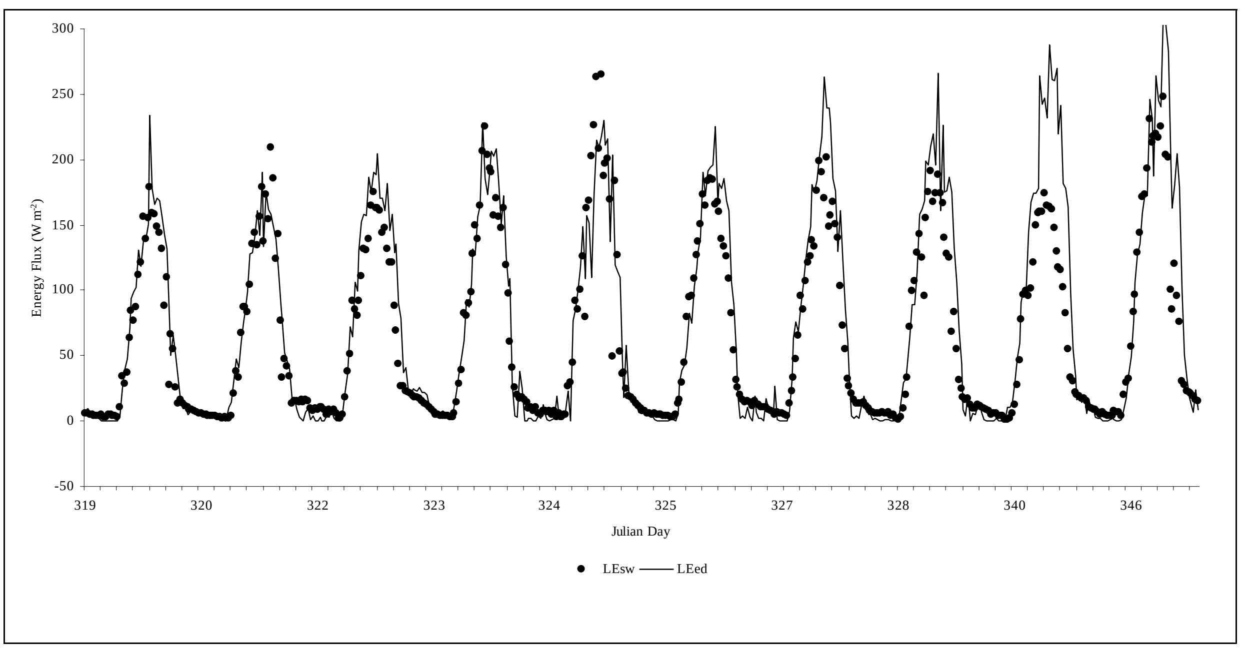


Figure 5. Daytime variation of latent heat flux (LE) obtained by the eddy correlation method (LE_{ed}) and computed by Shuttleworth and Wallace model (LE_{sw}) over a drip-irrigated Merlot vineyard.

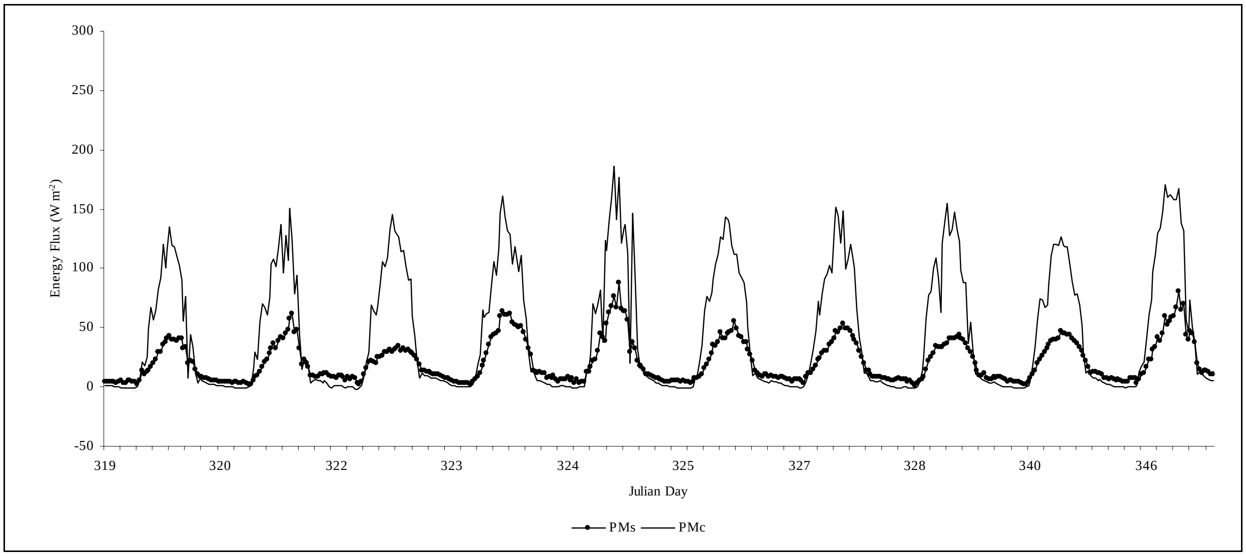


Figure 6. Daytime variation of transpiration (PMc) and evaporation (PMs) computed by Shuttleworth and Wallace model over a drip-irrigated Merlot vineyard.

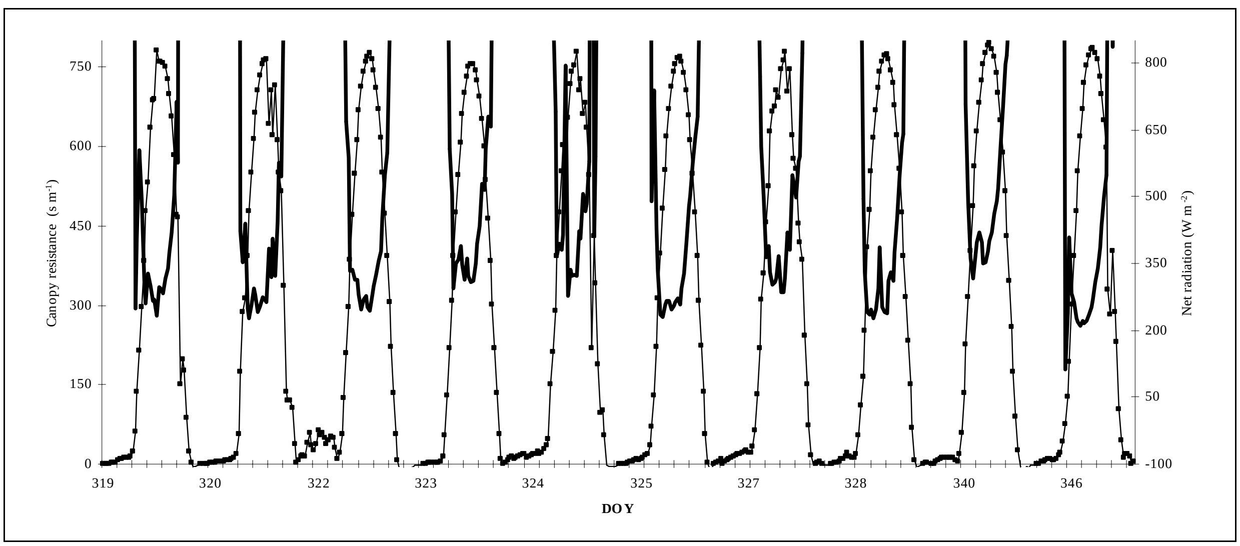


Figure 7. Daytime variation of canopy resistance (r_s^c) (average values from 10:00 to 15:00 h) for well-irrigated Merlot vineyard. The net radiation (Rn) is included as reference.

transpiration (Fig. 6). In this case, maximum values of PMc and PMs were 136-187 W m^{-2} and 33-86 W m^{-2}, respectively. The average PMc and PMs during the simulation period (10 days) were 1.7 mm day^{-1} and 0.7 mm day^{-1}, respectively (Fig. 6). On the other hand, soil evaporation measured by the microlysimeters ranged between 0.28 and 0.39 mm day^{-1}. The overestimation of soil evaporation by the SW model may be associated with the soil resistance which was set up as a constant during this study (2000 s m^{-1}). Also, it is important to indicate that the soil water content (SWC) in the root zone was maintained near field capacity (θ_i = 29%) and F was 0.73. For this level of SWC, the surface canopy resistance (average values from 10:00 to 15:00 h) ranged between 292 and 420 s m^{-1} (Fig. 7). The lowest value of r_c was observed on DOY 346, which presented measured and estimated values of ETa equal to 3.4 mm day^{-1} and 2.8 mm day^{-1}, respectively.

Best agreements between LE_{ed} and LE_{sw} at the Talca site were observed on DOY 320 where the regression slope was not significantly different from 1.0 and intercept was equal to 0 indicating that values of LE_{ed} were similar to those of LE_{sw}. Greatest disagreements were observed on DOY 340 (Fig. 5), where the SW model tended to underestimate LE with a MAE of 24 W m^{-2} and RMSE of 56 W m^{-2}. On this day, estimated and measured values of ETa were 2.5 mm d^{-1} (6.2 MJ $m^{-2}d^{-1}$) and 3.4 mm d^{-1} (8.4 MJ m^{-2} d^{-1}), respectively. Major disagreements were observed during the afternoon (between 16:00 and 18:00 h), where values of LE_{sw} were less than those of LE_{ed} with a maximum difference of 140 W m^{-2}.

CONCLUSIONS

The purpose of this study was to use the Shuttleworth and Wallace (SW) model to compute latent heat flux over a well-irrigated Merlot vineyard. The SW model (LE_{sw}) calculations were compared to those of the eddy-covariance method (LE_{ed}) on a 30 minute time interval. Model performance was good for the study period with the mean root square (RMSE) and mean absolute error (MAE) of 32 Wm^{-2} and 19 W m^{-2}, respectively. For the actual evapotranspiration, RMSE was 0.44 mm d^{-1} and MAE was 0.36 mm d^{-1}. Further research will be performed on modeling of the soil and canopy resistances to improve the estimation of soil evaporation and transpiration for vineyards under soil water stress.

ACKNOWLEDGEMENTS

The research leading to this report was supported by the Chilean project FONDECYT Nº 1030314 and a program for cooperation between Chile and France under project ECOS-CONICYT N° C04U03.

REFERENCES

Baldocchi DD, Hicks BB, Meyers TP (1988). Measuring biosphere–atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology 69:1331–1340

Heilman JL, McInnes KJ, Savage MJ, Gesch RW, Lascano RJ (1994) Soil and canopy balances in a west Texas vineyard. Agric For Meteorol 71: 99-114

Mayer, DG and Butler, DG (1993) Statistical validation. Ecological Modelling 68: 21-31.

McCarthy, M.G., 1997. The effect of transient water deficit on berry development of cv. Shiraz (*Vitis vinifera* L.). Austral. J. Grapewine Res. 3: 102-108.

Noilhan, J. and Planton, S. (1989). A simple parameterization of land surface processes for meteorological models. American Meteorological. Mon. Wea. Rev. 177: 536-549

Ortega-Farías, S., Duarte, M., Acevedo, A., Moreno, Y. and Córdova, F. 2004a. Effect of four levels of water application on grape composition and midday stem water potencial on Vitis Vinifera L. cv. Cabernet Sauvignon. Acta Hort. (ISHS) 664:491-497.

Ortega-Farias, S., Olioso, A. Antonioletti, R. and Brisson, N. 2004b. Evaluation of the Penman-Monteith model for estimating soybean evapotranspiration. Irri. Sci., 23: 1-9.

Ortega-Farias S, Olioso A, Fuentes S, and Valdes H. 2006. Latent heat flux over a furrow-irrigated tomato crop using Penman-Monteith equation with a variable surface canopy resistance. Agric. Water Mang. 82: 421-432.

Ortega-Farias, S., Carrasco, M., Olioso, A., Acevedo, C. And Poblete, C. 2007. Latent heat flux over a Cabernet Sauvignon Vineyard using the Shuttleworth and Wallace model. Irrig. Sci, 25: 161-170.

Sene KJ (1994) Parameterisations for energy transfers from a sparse vine crop. Agric For Meteorol 71: 1-18.

Spano D, Snyder RL, Duce P, Paw U KT (2000) Estimating sensible and latent heat flux densities from grapevine canopies using surface renewal. Agric For Meteorol 104: 171-183.

Shuttleworth WJ, Wallace JS (1985) Evaporation from sparse crops-an energy combination theory. Quart J.R. Met Soc 111:839-855.

Yunusa, I.A.M., Walker, R.R., and Lu, P (2004). Evapotranspiration components from energy balance, sapflow and microlysimetry techniques for an irrigated vineyard in inland Autralia. Agric and For Meteorol 127: 93-107.

ESTIMATING PECAN WATER USE THROUGH REMOTE SENSING IN LOWER RIO GRANDE

Zohrab Samani[1]
A. Salim Bawazir[2]
Max Bleiweiss[3]
Rhonda Skaggs[4]

ABSTRACT

Pecan is a major crop in Lower Rio Grande Basin. Currently there exist about 30,000 acres (12,000 ha) of pecan orchards at various stages of growth which consumes about 40 percent of irrigation water in the area. Crop evapotranspiration (ET) varies with age, soil type and method of management. The ET variation and lack of information on optimum crop ET result in significant variation in productivity and income. In order to maximize the returns from limited water resources, there is a need for a better understanding of pecan optimum ET. ET was measured using three eddy covariance flux towers, which were installed in selected fields in the irrigated area. This paper describes a process where remotely sensed data from ASTER were combined with ground level information to estimate pecan ET and crop coefficient (K_c) throughout the area. The measured cumulative annual pecan ET were determined as 1470 mm (4.82 ft) compared to a predicted value of 1415 mm (4.68 ft) using the remote sensing model. Regression summary for measured ET as depended variable resulted in Standard Error of Estimate (SEE) of 0.86 mm/day and adjusted R^2 of 0.9045 for 363 days of measured data.

INTRODUCTION

Dona Ana County, NM is ranked as No. 1 in the nation in pecan production. Currently, there are about 1,056 producers growing pecans in about 30,000 acres (12,000 ha). The state produces an average of 45 million pounds (20 million kg) of pecan annually with a value of about $100 million. Although water management is critical in the productivity of pecan, limited information is available on the spatial and temporal variability of water use by pecan. In addition, the question is complicated due to variation in pecan age, method of soil management, pruning and the carryover stress effect on pecan water use and yield.

Traditionally, ET has been calculated using crop coefficient (Kc) of pecan multiplied by reference evapotranspiration as:

---

[1]Professor, Civil Engineering Department; New Mexico State University, MSC 3CE, Box 30001, Las Cruces, NM 88003; zsamani@nmsu.edu
[2]Assistant Professor, Civil Engineering Department; New Mexico State University, MSC 3CE, Box 30001, Las Cruces, NM 88003; abawazir@nmsu.edu
[3]Science Specialist, Entomology, Plant Pathology and Weed Science Department, MSC 3BE, Box 30003, Las Cruces, NM 88003; mbleiwei@taipan.nmsu.edu
[4]Professor, Agricultural Economics & Agricultural Business, MSC 3BE, Box 30003, Las Cruces, NM 88003; rskaggs@nmsu.edu

$$ET = K_c \times ET_r \quad (1)$$

Where ET is the actual water use for the crop and ET_r is the reference evapotranspiration calculated from various equations such as Penman-Monteith (Allen, 1986), Blaney-Criddle (1950) or Hargreaves-Samani (1982, 1985, 1986). However, this traditional method of estimating pecan ET in New Mexico results in gross overestimation or underestimation of the true water use of the crop due to the variation in crop age, crop density, pruning, fertigation and lack of irrigation scheduling. This paper describes a remote sensing procedure for estimating real-time pecan ET in Lower Rio Grande Valley. The objective of this research was to evaluate the potential for application of remote sensing technology to evaluate the water use by various pecan orchards in Dona Ana County and to assess the potential for increasing the productivity of pecan in the area.

REMOTE SENSING MODEL

In this study, the Regional ET Estimation Model (REEM) (Samani et al, 2005) was used to calculate the daily ET for pecan orchards in Lower Rio Grande Valley. The model calculates the latent heat flux (LE) as a residual of the energy balance on surface:

$$LE = R_n - G - H \quad (2)$$

where, LE is the latent heat flux, R_n is the net radiation flux at the surface, G is the soil heat flux and H is the sensible heat flux to the air. All are in $MJ/m^{-2}day^{-1}$.

Daily net radiation over crop canopy was calculated using a methodology developed by Samani et al. (2005) as:

$$R_n = R_{ni}\left(\frac{R_s}{R_{si}}\right) \quad (3)$$

where, R_n is the daily net radiation in $MJm^{-2}day^{-1}$, R_s is daily short wave solar radiation in $MJm^{-2}day^{-1}$, R_{ni} is incident clear sky net radiation in W/m^2 at 11 am, and R_{si} is the incident short wave solar radiation in W/m^2 at 11 am.

The satellite data used in this study were from the Advanced Spaceborne Thermal Emission and Reflection (ASTER) radiometer on NASA's Terra satellite (Yamaguchi et al. 1998). It has a 60 km wide swath and a 16-day repeat cycle. However, data are not always available on a 16-day cycle at all locations. Satellite data from ASTER were used to calculate albedo, Normalized Difference Vegetation Index (NDVI) and surface temperature for the study area. The ASTER sensor makes multispectral observations in three wavelength regions which include visible to near infrared (VNIR), shortwave infrared (SWIR), and thermal infrared (TIR). The ASTER data used in this study came from the Land Processes Distributed Active Archive (LPDAAC) and consisted of the following:

AST_07 – Surface Reflectance (VNIR, SWIR) in the visible and near-infrared regions with 15 and 30 m spatial resolutions, respectively.
AST_08 – Surface Kinetic Temperature - 90 m spatial resolution

The data were time-referenced and annotated with ancillary information, including radiometric and geometric calibration coefficients, and geolocation information. In addition, the data were corrected for parameters such as atmospheric effects and variations in emissivity. The image processing software package ENVI® (Research Systems, Inc. Boulder, Colorado) and its many tools were used for data processing described here. The Normalized Difference Vegetation Index (NDVI) was calculated using ASTER sensor bands 3 and 2 as:

$$\mathrm{NDVI} = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2} \tag{4}$$

Where, ρ_i is the reflectance in band i.

Albedo (α) was calculated using the methodology described by Liang (2001):

$$\begin{aligned}\alpha = 0.484\rho_1 + 0.335\rho_3 - 0.324\rho_5 + 0.551\rho_6 \\ +0.305\rho_8 - 0.367\rho_9 - 0.0015\end{aligned} \tag{5}$$

Where, ρ_i is the reflectance in band i

The spectral range for various wavelengths used in the model are shown in table 1.

Incident net radiation (R_{ni}) values for the time of satellite overpass, which was about 11 AM (MST), were calculated using a modified form of Campbell (1977):

$$R_{ni} = (1-\alpha)R_{si} + \varepsilon_a \delta (T_a + 273)^4 - \varepsilon_0 \ \delta (T_c + 273)^4 \tag{6}$$

where R_{ni} is incident (instantaneous) net radiation (W/m²), R_{si} is incoming incident incoming short wave radiation (W/m²), α is surface albedo (dimensionless) , ε_a and ε_0 are dimensionless atmospheric and surface emmisivities respectively, and δ is the Stephan-Boltzmann constant (5.67×10^{-8} $MJm^{-2}K^{-4}$). T_a and T_c are incident near surface temperature and incident surface temperature respectively.

Incident Soil heat flux (G_i) at the time of satellite overpass was calculated using an equation recommended by Samani et al. (2005) as:

$$\frac{G_i}{R_{ni}} = 0.26e^{(-1.97\,\mathrm{NDVI})} \tag{7}$$

Choudhury (1991) recommended an equation similar to equation 7 where the ratio of G_i/R_{ni} was calculated from values of leaf area index (LAI). The incident sensible heat flux (Hi) was calculated by combining the aerodynamic equation with Monin-Obukhov similarity function (Tasumi 2003). The aerodynamic equation (Tasumi, 2003) is defined as

$$H_i = \rho_a C_p \frac{T_{as} - T_a}{r_{ah}} = \rho_a C_p \frac{\Delta T}{r_{ah}} \quad (8)$$

where ρ_a is the air density (kg/m^3), Cp is specific heat of air (1004 J/kg/K), T_{as} is the aerodynamic surface temperature in Kelvins (K), T_a is the air temperature (K), and rah is the aerodynamic surface resistance. Equation 7 was combined with Monin-Obukov function to solve for ΔT and r_{ah} using two reference points. A relationship was developed between ΔT and canopy temperature. The surface temperature values were used to calculate $\Delta T = T_{as} - T_a$ which was then used in equation 8 to calculate sensible heat for various pixels.

The evaporative fraction (E_f) for each pixel is defined as the ratio of the latent heat flux to the available energy and is calculated using the values of H_i, G_i, and R_{ni}:

$$E_f = \frac{R_{ni} - G_i - H_i}{R_{ni} - G_i} \quad (9)$$

Once the evaporative fraction is calculated and assuming that evaporative fraction is constant over the 24 hour period, the daily ET can be calculated by multiplying Ef by daily available energy as:

$$ET = E_f (R_n - G) \quad (10)$$

Assuming a negligible daily G value (Allen, 1998), daily ET can be calculated simply by multiplying Ef by the daily net radiation (R_n).

FIELD MEASUREMENTS

The eddy covariance technique, using one-propellor eddy covariance (OPEC) systems, was used on the towers to measure sensible heat (H) component of surface energy. The eddy covariance technique estimates sensible heat flux at the surface from the covariance between the fluctuations of vertical wind speed with temperature:

$$H = \rho c_p COV[wT] \quad (11)$$

Where, H is the sensible heat flux to the air (W/m^2) , ρ is the density of moist air (g/m^3), c_p is the heat capacity of air at constant pressure (J/g ^{o}C), w is the vertical air velocity (m/s), T is temperature of the air (^{o}C), *COV* is the covariance between w and T during the sampling period. Data were collected at 8 Hz and statistical summaries of 30-minute means processed online using battery powered CR23X data loggers (Campbell Scientific Inc.).

The OPEC sensors was placed about 7 m above the canopy. The ground heat flux (G) was measured using soil heat flux plates (model HFT3, REBS Inc.) under the plant canopies. The ground heat flux plates were placed about 1 cm in the ground at location that best represented both open and shaded canopies. Net radiation (R_n) was measured using net radiometers (Model Q7.1, REBS Inc.) mounted about 2.5 m above the canopy. The latent heat flux (LE) was determined using energy balance (equation 2)

RESULTS

Figure 1 compares the measured and predicted daily ET for a mature pecan orchard in Lower Rio Grande Valley. The daily ET values in figure 1 were measured by OPEC system. The estimated ET values were from REEM remote sensing model. The measured cumulative annual pecan ET was1470 mm or 4.82 ft compared with 1415 mm or 4.64 ft predicted from remote sensing model. Regression summary for measured ET as depended variable resulted in Standard Error of Estimate (SEE) of 0.86 mm/day, adjusted R^2 of 0.9045, and a slope and intercept of 1.03 and 0.03 respectively.

Figure 2 shows the variability of pecan water use in the valley. The variability is caused by pecan density, age, variety, and variation in nutrient and water availability. This demonstrates the value of real time large scale ET estimation compared to theoretical methods and/or point measurements.

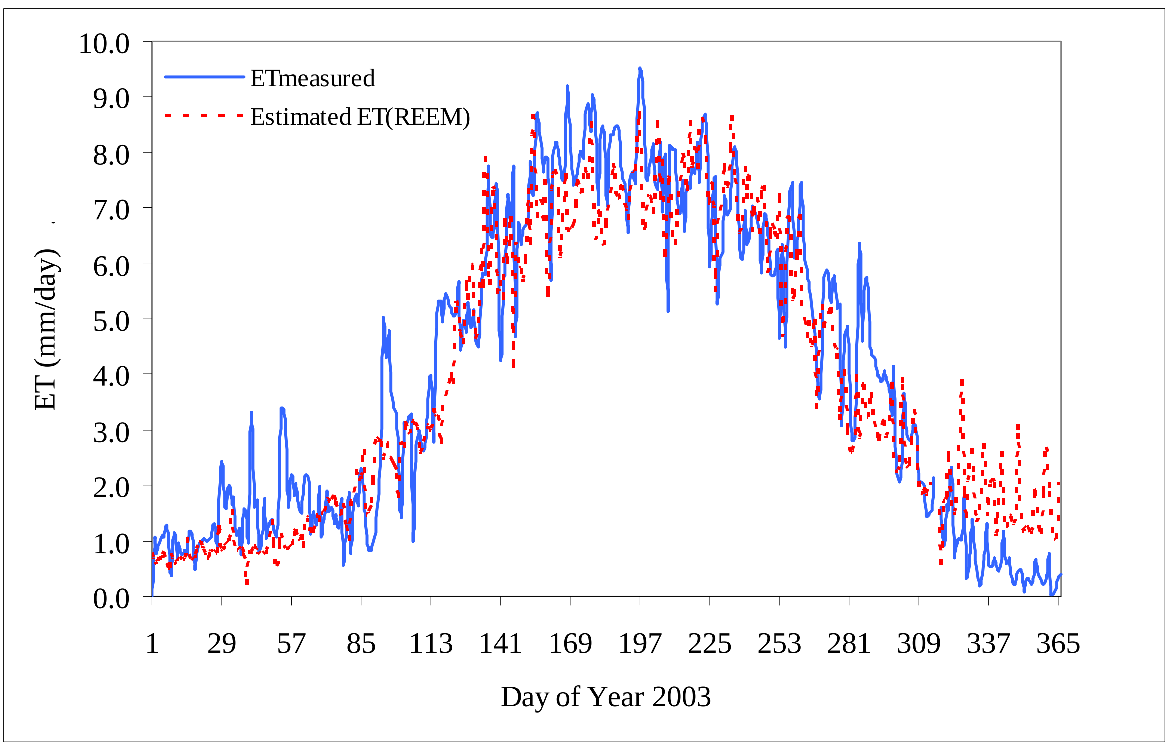


Figure 1. Measured and Predicted (REEM) Annual ET for a Mature Pecan Orchard in Lower Rio Grande Valley during Year 2003

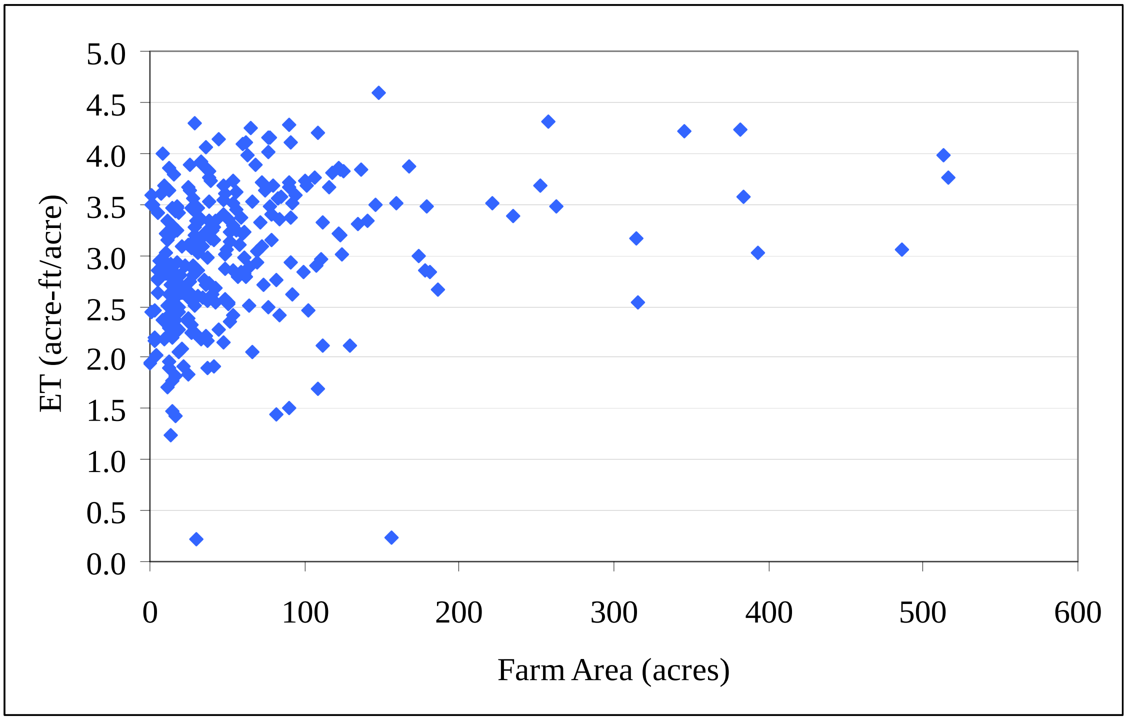


Figure 2. Annual ET (acre-ft/acre/year) Predicted (REEM) versus Individual Farm Acreage in Lower Rio Grande Valley

CONCLUSION

Results from this study showed that remote sensing could estimate pecan water use in the Lower Rio Grande reasonably well. The measured cumulative annual pecan ET were determined as 1470 mm (4.82 ft) compared with 1415 mm (4.64 ft) predicted from remote sensing model. Regression summary for measured ET as depended variable resulted in Standard Error of Estimate (SEE) of 0.86 mm/day and adjusted R^2 of 0.9045 for 363 days of measured data. The largest error occurred during December. This error was caused by lack of available satellite images. Water use by pecan orchards varied spatially and temporally.

Table 1. Wavelengths for various spectral bands in ASTER

Subsystem	Band No.	Spectral range (µm)	Spatial Resolution (m)
VNIR	**1**	**0.52-0.6**	**15**
	2	**0.63-0.69**	
	3	**0.76-0.86**	
SWIR	**4**	**1.600-1.700**	**30**
	5	**2.145-2.185**	
	6	**2.185-2.225**	
	7	**2.235-2.285**	
	8	**2.295-2.365**	
	9	**2.360-2.430**	
TIR	**10**	**8.125-8.475**	**90**
	11	**8.475-8.825**	
	12	**8.925-9.275**	
	13	**10.25-10.95**	
	14	**10.95-11.65**	

ACKNOWLEDGMENT

Our acknowledgment extends to New Mexico Office of State Engineer, Western Pecan Growers, Rio Grande Basin Initiative, Stahmann Farms Inc., NFS-EPSCoR, and Students Atzuko Reveles, Vien D. Tran, Eric Lopez, Brad Kirksey, Jose Solis for their support and contribution to this study

REFERENCES

Allen, R.G. 1986. A penman for all seasons. J. Irrig. and Drain. Engrg. 112(4).

Allen, R. G., Walter, I. A., Elliot, R., Itenfisu, D., Brown, P., Jensen, M. E., Mecham, B. et al. (2003). “The ASCE Standardized Reference Evapotranspiration Equation.” International Conference on Irrigation and Drainage (2^{nd} 2003: Phoenix, AZ.). *Water for a Sustainable World-limited Supplies and Expanding Demand*. U.S. Committee on Irrigation and Drainage, Denver, p. 593-602.

Blaney, H.F., and Criddle, W.D. 1950. Determining water requirements in irrigated areas from climatological and irrigation data. USDA Soil Conserv. Serv. SCS-TP96. 44p.

Choudhury, B. J. 1991. Multispectral satellite data in the context of land surface heat balance. *Review of Geophysics*, 29:217-236.

Hargreaves, G.H. and Z.A. Samani 1982. Estimating potential evapotranspiration. J. Irrig. and Drain. Engrg. 108 (IR3), September 1982

Hargreaves, G. H. and Z. A. Samani 1985. Reference crop evapotranspiration from temperature. Journal of Applied Engineering in Agriculture, Vol. 1, No.2.

Liang S., C.J. Shuey, A. L. Russ, H. Fang, M. Chen, C.L. Walthalk, C.S.T. Daughtry, R Hunt Jr. 2002. Elsevier 84(2002) 25-41.

LPDAAC – http://lpdaac.usgs.gov/main.asp

Tasumi, M. 2003. *Progress in operational estimation of regional evapotranspiration using satellite imagery*. Ph.D. diss. Moscow, Idaho: University of Idaho. 357p.

Samani, Z. A. and G. H. Hargreaves 1986. Discussion on "Data requirements for evapotranspiration estimation”. Journal of Irrigation and Drainage Engineering, ASCE, Vol. 11, No.4 December 1986.

Samani, Z, Nolin, S., Bleiweiss, M., and Skaggs, R. 2005. Discussion of “PredictingDaily Net Radiation Using Minimum Climatological Data,” *Journal of Irrigation and Drainage Engineering*, 131(4): 338-389.

Yamaguchi, Y., Kahle, A. B., Tsu, H., Kawakami, T., and Pniel, M. 1998. Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) *IEEE Transactions on Geoscience and Remote Sensing*, 36:1062-1071.

THE IMPACT OF SPATIAL VARIATION OF WEATHER PARAMETERS IN MOUNTAINOUS AREAS ON REFERENCE ET ESTIMATION

Masahiro Tasumi[1]
Shinichi Takeshita[2]
Richard G. Allen[3]
Ricardo Trezza[4]

ABSTRACT

Reference evapotranspiration (ET_o) is frequently estimated when investigating the regional hydrologic cycle. In mountainous regions, calculation of ET_o is challenging, because of the complicated mountainous terrains that generate large spatial variability (or uncertainty) in solar radiation and in other weather parameters such as air temperature and wind speed. Moreover, obtaining quality weather data is difficult in mountains. Unlike lowland city and agricultural areas, public weather stations are rarely installed in mountains.

In this study, a widely accepted standardized Penman-Monteith equation is applied to estimate ET_o with the spatial variation in mountainous regions. The study area is in Miyazaki, Japan. The solar radiation estimation procedure by Allen et al. (2006) is incorporated into the ET_o estimation and its impact on the accuracy of estimated ET_o is evaluated. The procedure accounts for the land-surface slope and orientation when estimating solar radiation, which is an improvement from the traditional reference-ET applications in mountains. When estimating ET_o in mountainous regions, quantifying the error of ET_o caused by local weather is also important. In this study, we conduct sensitivity analysis to quantify the expected accuracy level of calculated ET_o in mountain.

Keywords: reference evapotranspiration, solar radiation, hydrology, DEM

INTRODUCTION

Potential evapotranspiration (ET_{pot}) and reference evapotranspiration (ET_o) are commonly used parameters for estimation of evapotranspiration (ET) in basin-scale hydrological modeling. ET_{pot} refers to maximum meteorologically evaporative power on the land surface. ET_o is the term similar to ET_{pot}, but the physical properties of evaporative surface are more strictly defined. ET_{pot} is a more popularly used term in hydrology, but using ET_o is recommended (Allen et al.,

[1]Associate Professor, University of Miyazaki, 1-1, Gakuen Kibanadai-Nishi, Miyazaki 889-2192, JAPAN; tasumi@cc.miyazaki-u.ac.jp
[2]Assistant Professor, University of Miyazaki, 1-1, Gakuen Kibanadai-Nishi, Miyazaki 889-2192, JAPAN; rtakeshita@cc.miyazaki-u.ac.jp
[3]Professor, University of Idaho, 3793N, 3600E, Kimberly, ID 83341; rallen@kimberly.uidaho.edu
[4]Professor, Universidad de los Andes, Merida, Venezuela; rtrezza@ula.ve

1998) to avoid confusion caused by the ambiguities in the definition of evaporative surface. ET_o is calculated by weather data only. ET_o, with some adjustments, is frequently used as a basis in basin-scale hydrological models as actual ET. Although accuracy is questionable, there is no other convenient alternative for estimating actual ET for a wide area. Gong et al. (2006) indicated that among the major input weather parameters of ET_o, wind speed is not sensitive to ET_o computation compared to vapor pressure, solar radiation and air temperature.

In basin-scale applications, ET_o is generally applied to a wide extent of area. In such case, accuracy depends on the variation of weather and the topographic characteristics in the area of interest. Traditionally, basin-scale ET_o applications do not consider effect of surface slope on evaluating solar radiation (e.g.: Hickel and Zhang, 2006; Kannan et al., 2007; Melkonian et al., 2007). No previous research on this topic has been found. In this study, the impact of spatial variation of solar radiation on ET_o was evaluated using a Digital Elevation Model (DEM) and GIS technique. Another problem in basin-scale applications is the sparse distribution of public weather stations. Namely, weather stations are rarely available in mountainous regions, while they may be densely installed in lowlands cities and agricultural areas. Thus, large errors in input weather parameters are sometimes inevitable in mountain areas even if the input weather parameters are interpolated using data from multiple lowland weather stations. In this study, the impact of weather parameters on ET_o estimation and accuracy are evaluated in basin-scale applications.

METHODOLOGY

We calculated grass-reference evapotranspiration (ET_o) of the study area of Miyazaki, Japan, using a standardized Penman-Monteith equation following the manual by American Society of Civil Engineers (ASCE-EWRI., 2005). ET_o is defined as evapotranspiration from a hypothetical 12-cm clipped, cool-season grass in well-watered condition.

Study Area and Data Used

The study area is located around Miyazaki City (Figure 1). The area has elevation range of 0 to 1200 m. Among the five weather stations operated inside of the study area by the Japan Meteorological Agency, only the “Miyazaki” station measures all necessary weather data for ET_o calculation. Four other stations neither measure solar radiation (R_s) nor vapor pressure (e_a). All of these five stations are located in lowland city or town. No station is available in the mountainous area. Thus, accuracy of weather data in mountains is somewhat questionable although more than half of the study site is categorized as mountainous. In this study, weather data from the Miyazaki station was applied to calculate ET_o, and the data from four other stations were occasionally used to understand the variation of weather in the study area. A 50 m DEM by Geographical Survey Institute of Japan is the most popular DEM source in Japan. The original pixel size of the DEM is 1/1600 by 1/2400 degrees, which is equivalent to 59 m (East-West) by 46 m (North-South) around Miyazaki. The DEM was used in this study after reprojecting to 30m pixel-size using bi-linear interpolation.

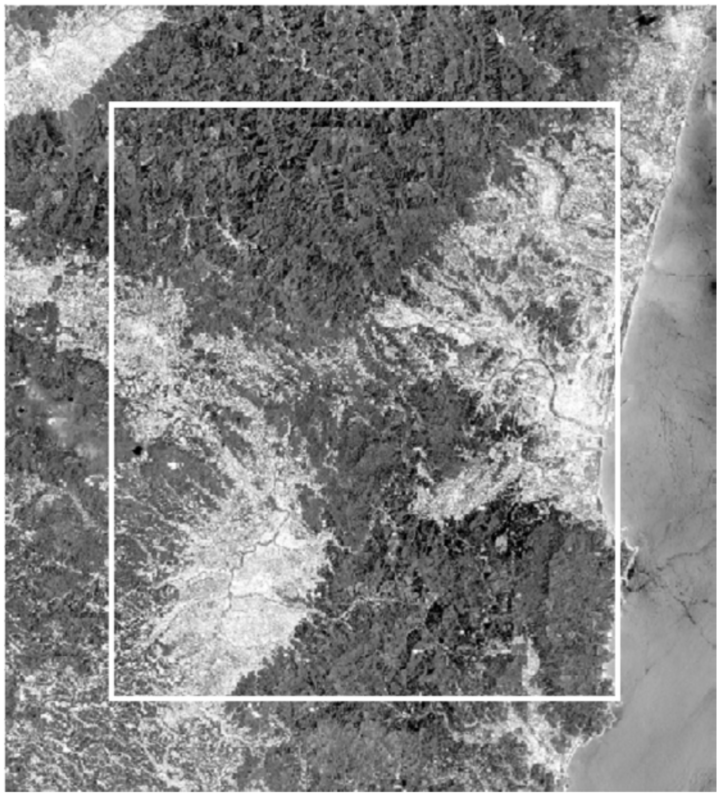


Figure 1. Study area (Miyazaki, Japan 31°56'N/131°25'E; 50 km by 60 km)

Solar Radiation and ET_{ref} Calculation

Solar radiation (R_s) was calculated using the analytical translation algorithm developed by Allen et al (2006) for 24-hour periods and the numerical application procedure summarized by Tasumi et al (2006). These procedures estimate solar radiation for slopes with commensurate estimates of diffuse radiation from the sky. In the numerical application, DEM of the study area, and hourly R_s and e_a measured at Miyazaki station were the input data. The numerical procedure estimates R_s for any sloping surface by analyzing the relative solar incidence angle (θ_{rel}; the angle between the solar beam and a vertical line perpendicular to the land surface) for each 30 minute time interval. θ_{rel} is calculated by the following standard equation of Duffie and Beckman (1991):

$$\begin{aligned}\cos\theta_{(rel)} &= \sin(\delta)\sin(\phi)\cos(s) - \sin(\delta)\cos(\phi)\sin(s)\cos(\gamma) \\ &+ \cos(\delta)\cos(\phi)\cos(s)\cos(\omega) \\ &+ \cos(\delta)\sin(\phi)\sin(s)\cos(\gamma)\cos(\omega) \\ &+ \cos(\delta)\sin(s)\sin(\gamma)\sin(\omega)\end{aligned} \quad (1)$$

where δ is declination of the earth (positive in summer in the northern hemisphere), ϕ is latitude of the pixel (positive for the northern hemisphere and negative for the southern hemisphere) that can be a constant except when the processing area is too large, s is surface slope where s = 0 for horizontal and s =π/2 radians for vertical downward slope (s is always positive and represents the downward slope in any direction), γ is the surface aspect angle, where $\gamma = 0$ for slopes oriented due south, $\gamma = -\pi/2$ radians for slopes oriented due east, $\gamma = +\pi/2$ radians for slopes oriented due west and $\gamma = \pm \pi$ radians for slopes oriented due north. Parameter ω is the hour angle, radians, where $\omega = 0$ at solar noon, ω is negative in morning and ω is positive in afternoon.

ET_o was calculated using the ASCE standardized Penman-Monteith equation (ASCE-EWRI, 2005). Computation was made on a 24-hour time step. Input data were measured daily maximum and minimum T_{air}, daily maximum and minimum relative humidity, daily average wind speed, DEM for air-pressure estimation and 24-hour R_s estimated by the above-mentioned procedure. The ASCE standardized equation is defined as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2)$$

where R_n is calculated net radiation at the crop surface (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}) approximated as zero for daily period, T is mean daily air temperature at 1.5m to 2.5m height (^oC), u_2 is mean daily wind speed at 2 m height (m s^{-1}), e_s and e_a are saturation and mean actual vapor pressure at 1.5m to 2.5m height (kPa), Δ is slope of the saturation vapor pressure-temperature curve (kPa $^oC^{-1}$), γ is psychrometric constant (kPa $^oC^{-1}$).

In spatial estimation of ET_o, the measured T_{air} at Miyazaki station was adjusted for elevation difference using the standard environmental lapse rate of 6.5^{o}C per km. e_a was also decreased with elevation assuming relative humidity is constant in the study area, which might be a reasonable assumption in a humid or sub-humid climate where relative humidity is high. No adjustment was made for wind speed. The applicability of the Allen et al. (2006) R_s estimation procedure and ASCE's ET_o equation are not limited to clear-sky. However, in this study, three clear-sky days were selected for evaluation in order to simplify the analyses. The three selected dates were June13, Sept. 23 and Dec. 22 of 2005, which were the nearest clear-sky dates from the summer solstice, fall equinox and winter solstice respectively. Evaluation of cloudy conditions will be considered in a future study. All calculations were made using ERDAS Imagine remote-sensing software. Figure 2 shows a snapshot of the program developed during this study.

RESULTS

Figure 3 shows calculated instantaneous R_s near the peak of a mountain at Sept. 25, 2005. The sun was in the southeast at 9:00 in the morning (solar elevation = 35^o), thus the east side of the peak received about 500 W/m^2 more solar radiation than the west side. The sun was in the south at noon (solar elevation = 56^o), thus the south side of the peak received more radiation than the north side. In evening, the sun was from the southwest (solar elevation = 35^o) and south-facing slopes received more radiation. Similar hourly trends in R_s were found for all investigated dates.

Over 24 hour time periods, the south side of the peak received about 100 W/m^2 more R_s than the north side in the case of Sept.25 and Dec. 22, 2005. The difference in R_s caused by surface slope was much less obvious in the summer image.

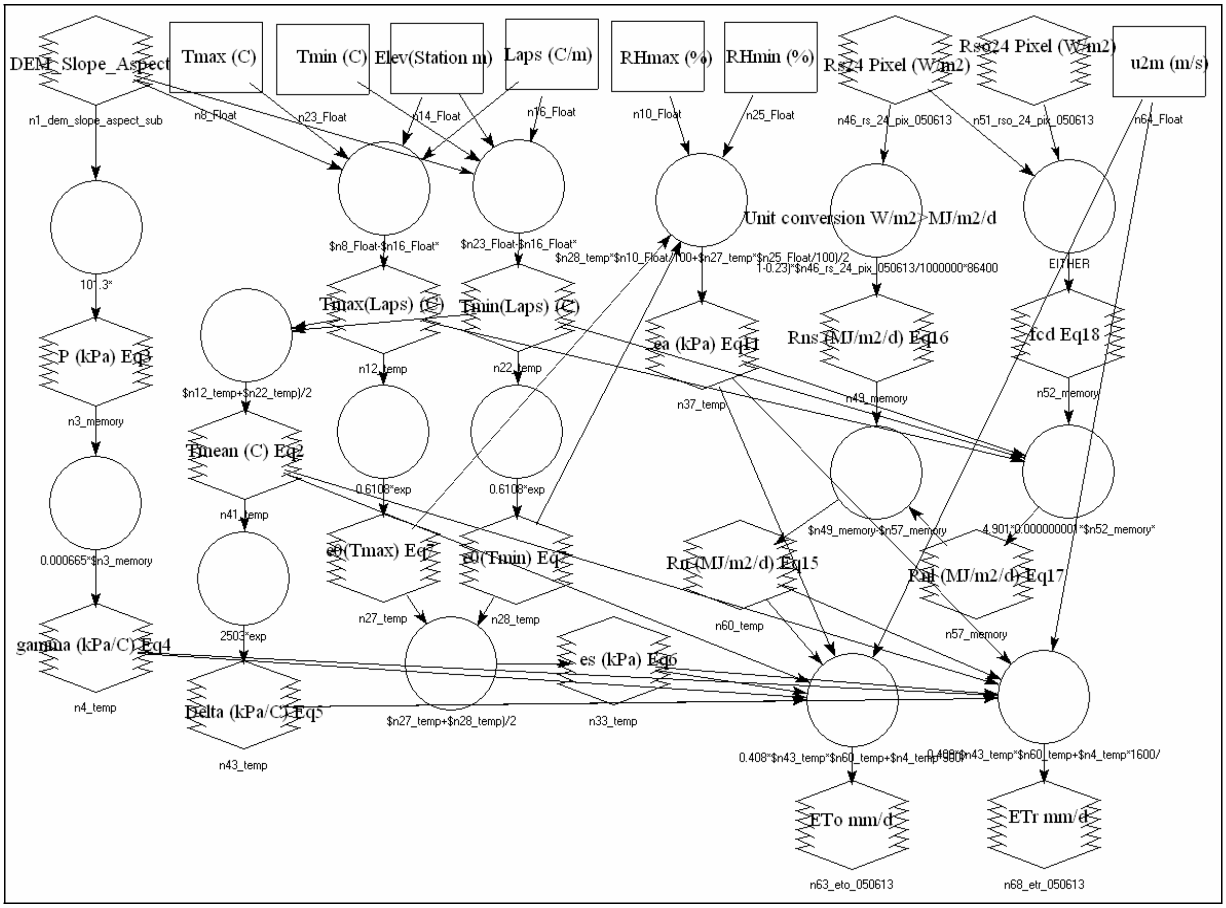


Figure 2. ERDAS Imagine submodel for calculating reference ET on slopes.

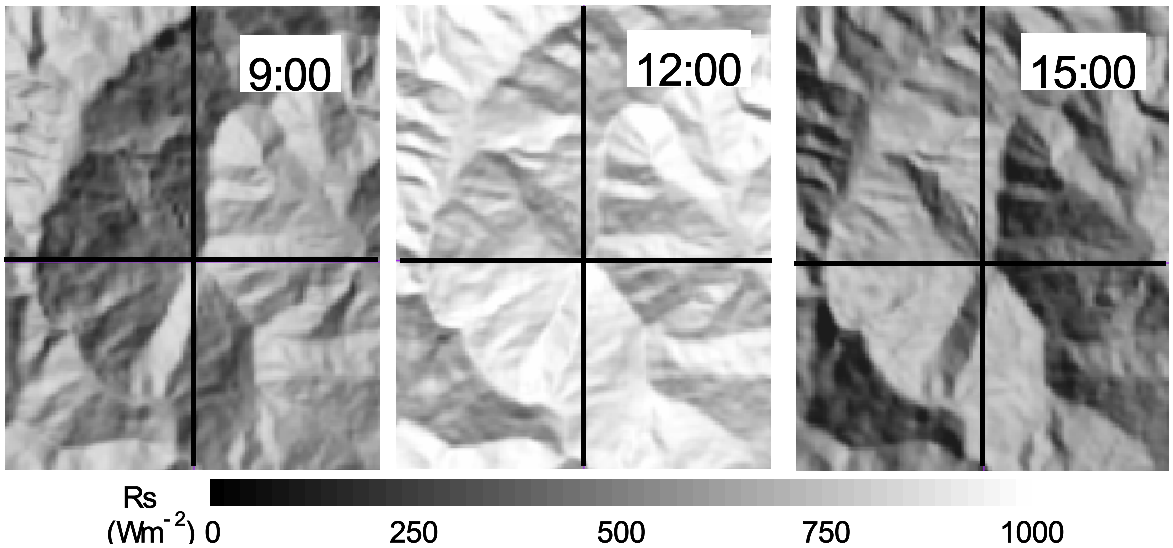


Figure 3. Estimated hourly solar radiation for 9:00 in the morning (solar elevation = 35°), 12:00 noon (56°) and 16:00 in the afternoon (35°) of Sept. 25, 2005, at 31°43.3'N/131°16.8'E.

Figure 4 shows estimated ET_o in a mountainous area for June 13, Sept. 25 and Dec. 18. If the DEM were not applied in the ET_o estimation, the estimated ET_o for the day would be constant over the area. The significant impact of using the DEM was illustrated for all three evaluated days (two different types of impacts were confirmed). On June 13, ET_o over the study area varied from 5 mm to 6 mm. Visual evaluation showed that the spatial variation of ET_o was strongly correlated to elevation, rather than to surface slope and the orientation. June 13 was close to the summer solstice when the average solar elevation was the highest. Thus the relative impact of surface slope/aspect to R_s was near a minimum and the spatial variation in ET_o was derived mostly by the difference of air temperature expressed by standard environmental lapse rate (and estimated reduction in vapor pressure with elevation). On the other hand, spatial variation in ET_o was strongly correlated to the surface slope and the orientation on Sept. 25 and Dec. 18. On these days, the solar elevation was lower than for June 13, and thus surface slope and aspect had a larger impact on variation in R_s. At any rate, the results clearly indicate the importance of considering surface elevation and slope when estimating ET_o in mountainous areas. More detailed discussion is made in a later section on sensitivity analysis.

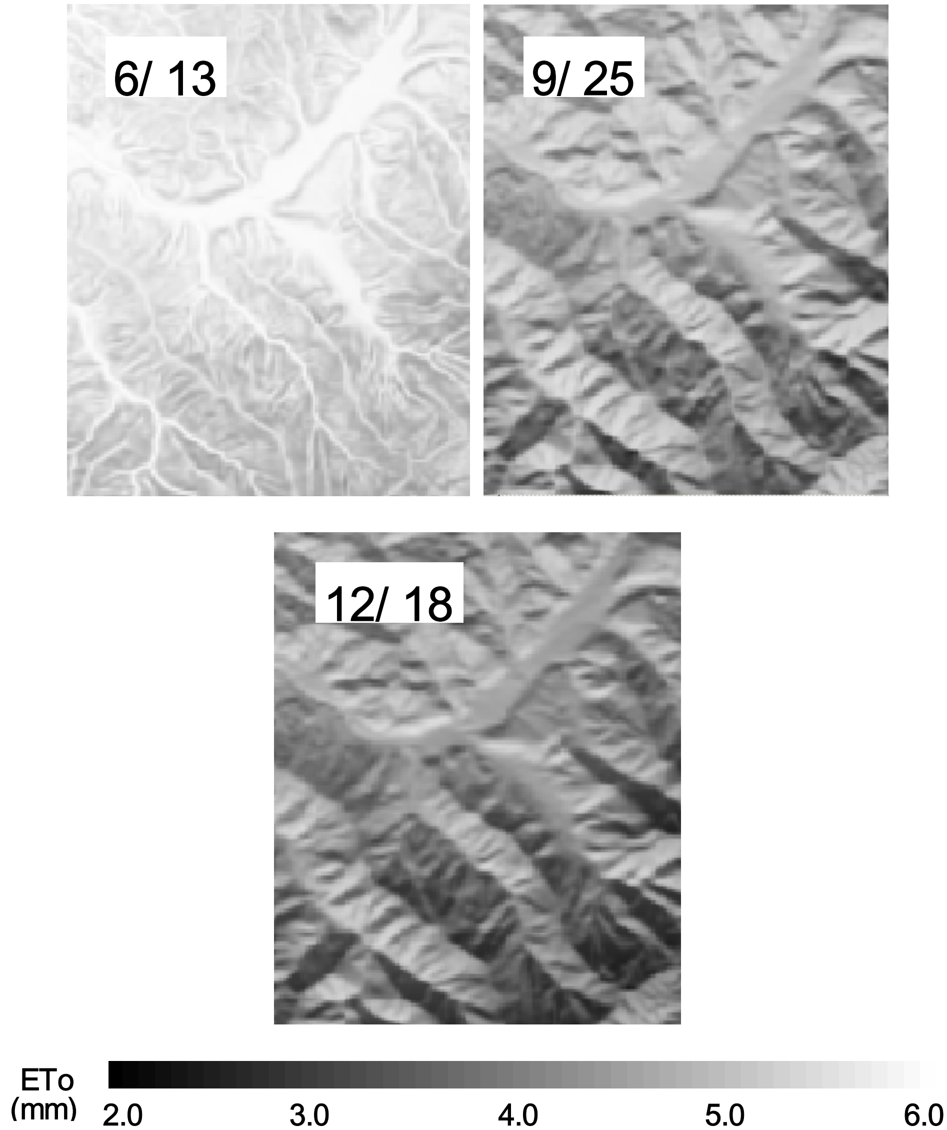


Figure 4. 24-hour ETo in a mountainous area on June13, Sept. 25 and Dec. 18.

SENSITIVITY ANALYSIS

Spatial application of ET_o computations in mountainous regions contains several uncertainties in estimation of solar radiation and other input weather parameters. Error analysis is not easy because all input parameters are interrelated, and the impact of a parameter on ET_o changes with the topographic and weather properties of each site. In this study, sensitivity analysis was made for R_s, temperature, humidity and wind speed.

Land Surface Slope and Aspect

Figure 5 shows the impact of surface slope and aspect on solar radiation for the three study days at Miyazaki. In the R_s computation, all other input atmospheric properties were fixed to make the surface slope and aspect the only variables. On June 13, no significant variation in R_s was observed when slope ranged from zero to 30^o. Because the majority of surface slopes in the study area were below 30^o, surface slope and aspect did not have significant impact on 24-hour R_s. The result of the sensitivity analysis agreed with the discussion made for Figure 4 in the previous section. On the other hand, south-facing slopes received much higher R_s compared to north facing slopes on Sept. 25 and Dec. 18 (fall equinox and winter solstice). The variation in R_s directly affected the ET_o computation on these dates as shown in Figure 6. Within the three evaluated dates, the impact of surface slope and aspect to ET_o were large on Sept. 25 and Dec. 18. For these dates, the difference of ET_o between south and north facing slopes was about 1 to 2 mm/day for slopes of 10^o to 30^o.

There is one caution on understanding the results shown in Figures 5 and 6. R_s and ET_o values given in Figures 5 and 6 correspond to actual sloping surface area. On the other hand, in many GIS applications, surface areas are treated or expressed as a "horizontal projected" area. For example, one 30 m by 30 m GIS raster pixel has 900 m^2 actual surface area if the surface has no slope, but $900/\cos(30^o) = 1039$ m^2 actual surface area if the surface has 30^o slope. For a unit-projected area, actual surface area is greater as the surface slope is greater. The impact of slope and aspect presented in Figures 5 and 6 are even more enhanced if they are based on horizontal projected surface areas.

Air Temperature and Vapor Pressure

Next, the impact of air temperature (T_{air}) and vapor pressure (e_a) on ET_o was evaluated. Miyazaki has a humid climate, thus T_{air} and e_a are strongly interrelated as indicated in Figure 7. The 95% confidence interval shown in the figure indicates that the variation of daily e_a for a daily T_{air} was nearly constant (about 0.85 kPa) in Miyazaki. The impact of T_{air} and e_a on ET_o was evaluated using an estimated interrelation between T_{air} and e_a. The result of the sensitivity analysis is shown in Figure 8, where ET_o was calculated for various T_{air} and e_a combinations by fixing wind speed (u), R_s and R_s/R_{so} ratios (u = 3.41m/s, R_s = 15.3 MJ/m2, R_s/R_{so} = 0.68, which are annual averages for Miyazaki, 2005). The result in Figure 8 indicates that the impacts of T_{air} and e_a should not be ignored. In the study area, spatial variation in T_{air} was small if limited to lowland areas. Five lowland weather stations were spread over the study area, and the maximum difference in daily T_{air} observed at the five stations was only 1.4^oC (1σ), which does not affect ET_o estimation much over all temperature and humidity conditions (Figure 8). However, the problem will be more in mountainous regions. The elevation of the study area varies from zero at seaside to 1200 m in the mountains, which is equivalent to 7.8^oC difference in temperature if the standard environmental lapse rate is assumed. According to the results in Figure 8, a 7.8^oC difference in T_{air} resulted in 2 mm/day difference in ET_o under high-temperature and humid conditions. In addition to the lapse effect, mountainous terrain tends to generate specific local weather that might enhance the spatial variation in T_{air}.

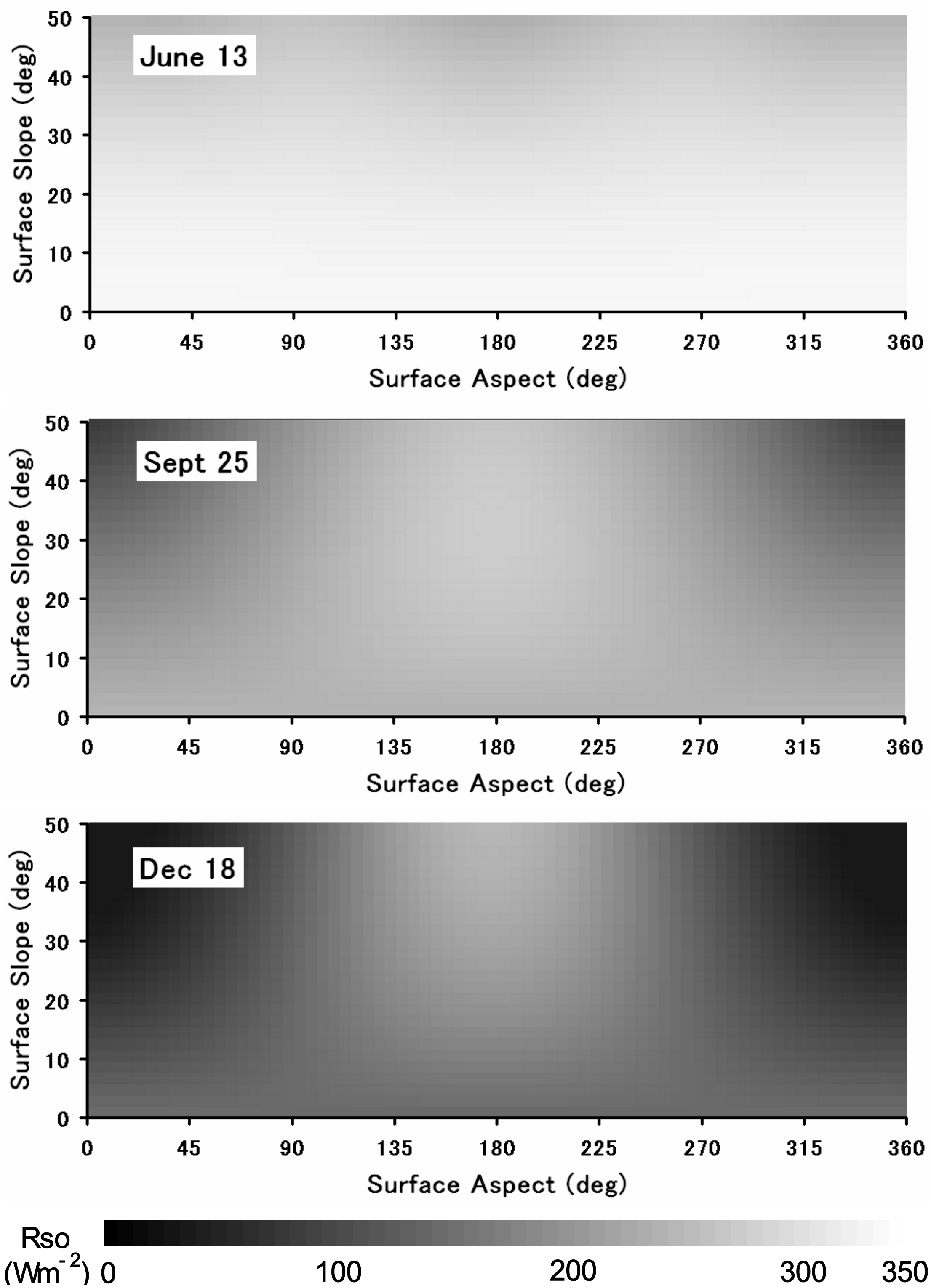


Figure 5. Range and variation of calculated 24-hour solar radiation (for clear sky) with variation in surface slope and slope orientation in June 13, Sept. 25 and Dec. 18 of 2005, Miyazaki, Japan.

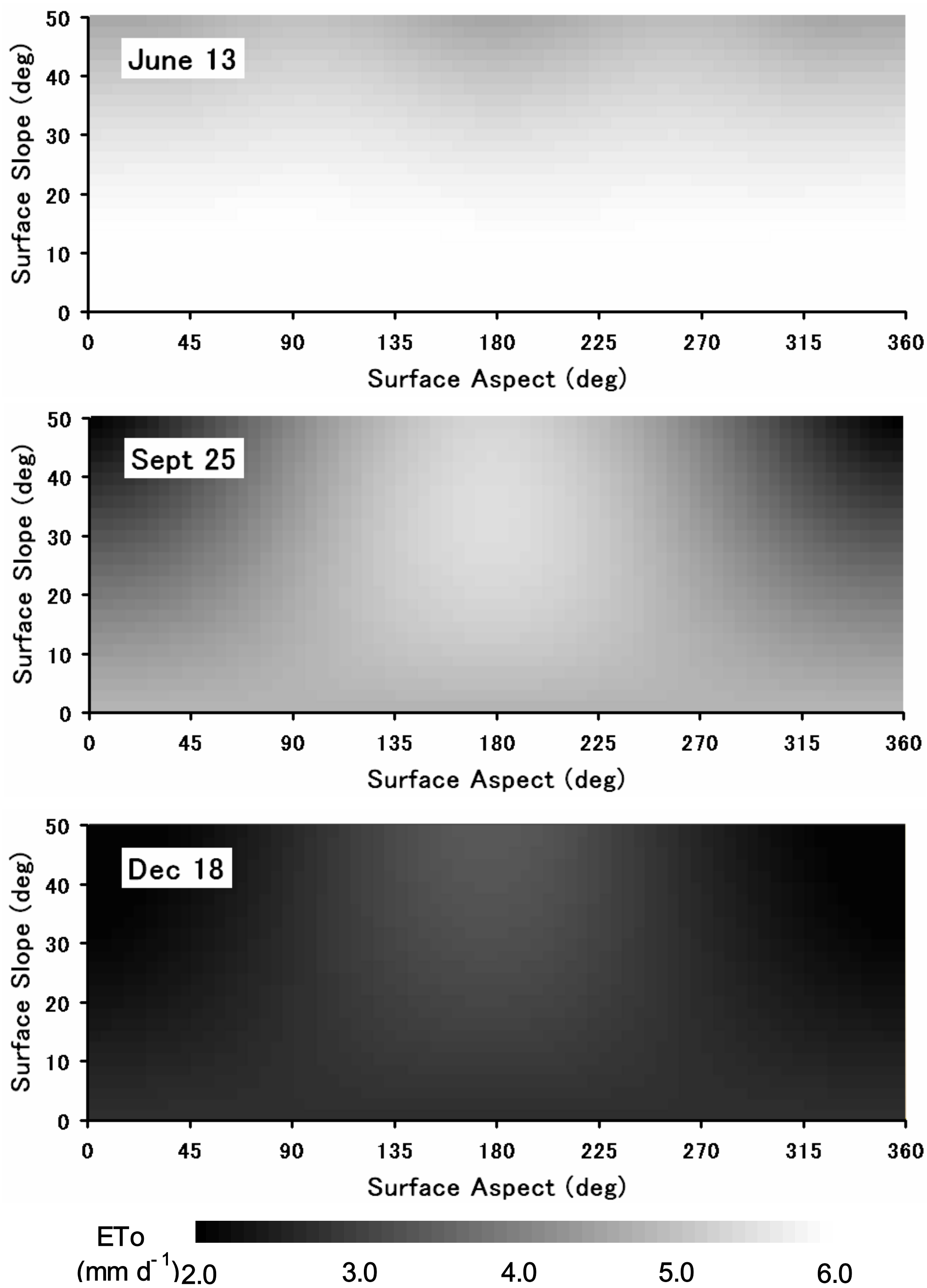


Figure 6. Range and variation in calculated ET_o due to variation in solar radiation caused by variation in surface slope and slope orientation in June 13, Sept. 25 and Dec. 18 of 2005, Miyazaki, Japan.

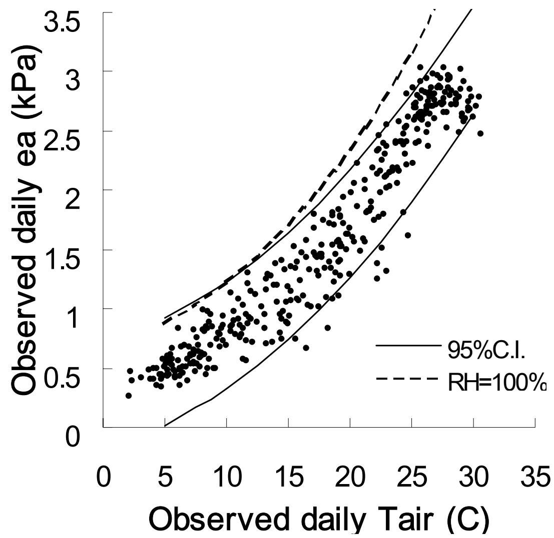


Figure 7. Daily air temperature and vapor pressure observed at Miyazaki station from Jan. 1 to Dec. 31, 2005. The two solid lines in the figure indicate the 95% confidence interval.

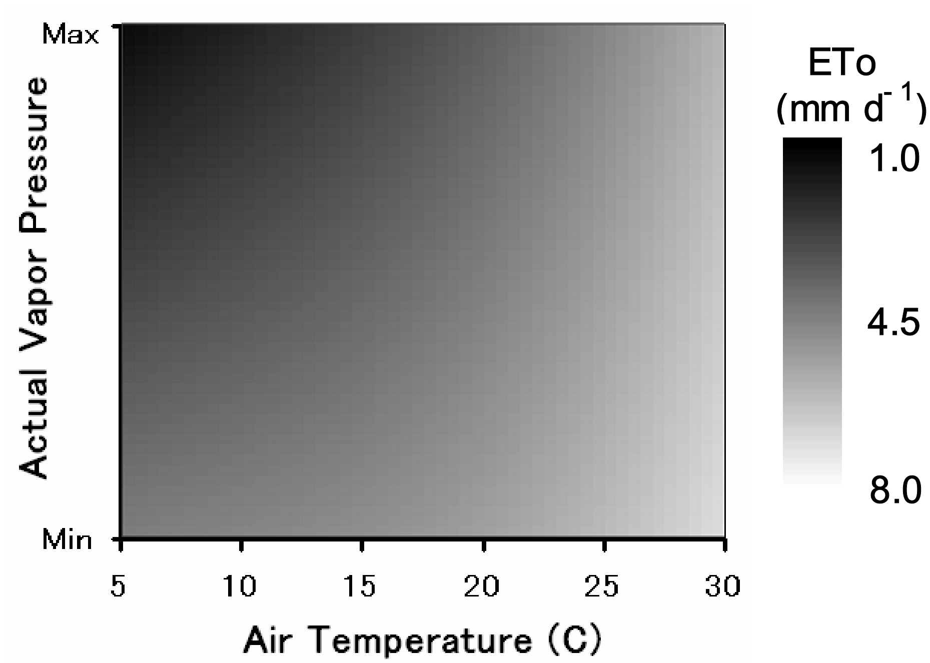


Figure 8. Sensitivity of ET_o to air temperature and vapor pressure (all season). “Min” and “Max” in vapor pressure are the top and bottom 95% confidence interval in Figure 7 (i.e. min and max vapor pressure changes by T_{air}).

Wind Speed

In Miyazaki, 95% of the daily wind speed (at 2 m about the ground) was within the range of 0.7 and 6.1 m/s during 2005. Figure 9 shows the results of calculated ET_o for the range of wind speed and for air temperature range of 5 to 30^oC. In the sensitive analysis, average conditions for R_s and R_s/R_{so} for Miyazaki were applied, and a representative value for e_a was assigned for each T_{air}. As shown in Figure 9, ET_o was not very sensitive to wind speed due to the relatively high e_a and low vapor pressure deficit of the humid climate. This result agrees with the results from a previous study by Gong et al. (2006). However, ET_o might be more sensitive to wind speed in an arid environment due to the multiplicative wind speed and vapor pressure deficit term in the Penman-Monteith equation. Figure 9 implies an interesting consequence related to the effect of elevation. ET_o increases as wind speed or T_{air} increases. In mountains, wind speed tends to increase and T_{air} tends to decrease as elevation increases. This means that wind speed and T_{air} have opposite effects with increasing elevation in mountains. Therefore in mountain regions, error in ET_o caused by applying lowland weather data might be reduced or moderated because of the interaction between T_{air} and wind speed.

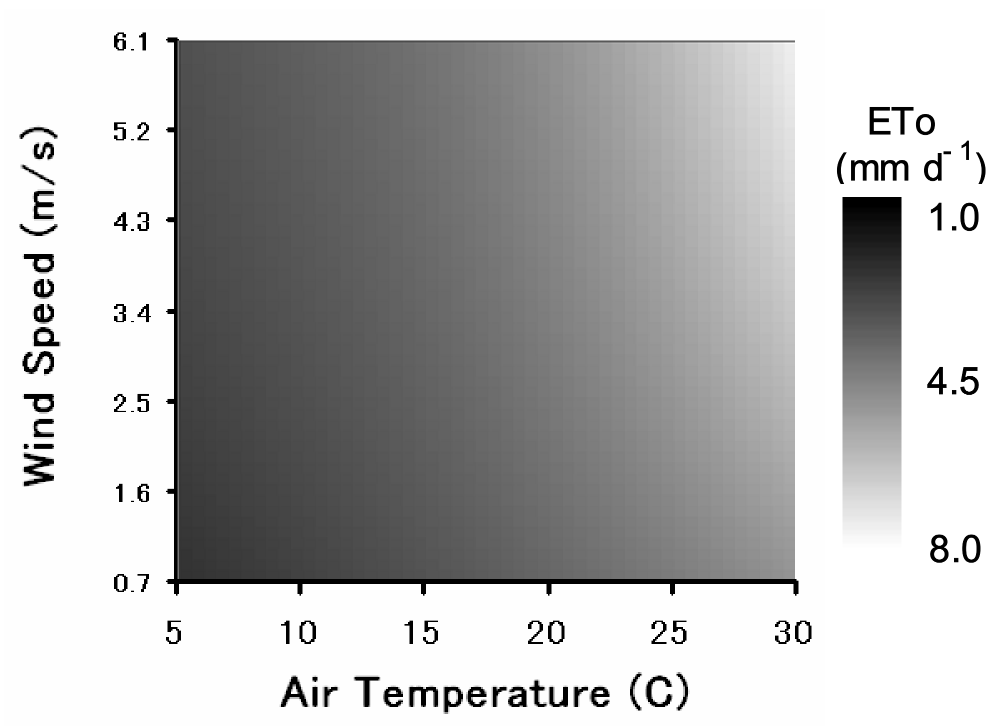


Figure 9. Sensitivity of ET_o to wind speed in Miyazaki.

SUMMARY AND CONCLUSION

Reference evapotranspiration (ET_o) is a commonly used parameter in basin-scale hydrological modeling. However, the application of ET_o on a basin scale has potential problems and complications regarding the determination of solar radiation and other input weather parameters that are typically measured in lowlands. This study investigated the topographic impacts on solar radiation and further to grass-reference evapotranspiration (ET_o) in Miyazaki, Japan. The topographic impact was lowest in mid summer when solar elevation was high, but it was significant in fall and winter. ET_o for south facing slopes was 1 to 2 mm/day greater than that for north facing slopes in fall and winter. Although further studies for cloudy conditions are recommended, including a topographic effect on estimating ET_o should improve ET estimation in mountainous regions. Sensitivity analysis for temperature and vapor pressure indicate that ET_o is sensitive to these parameters in the mountainous region of Miyazaki. ET_o was determined to not be very sensitive to wind speed under humid climates similar to that of Miyazaki. The results of sensitivity analysis illustrated the potential error range of estimated ET_o in mountainous areas where weather parameters are typically estimated using weather data measured at lowland cities and agricultural areas.

ACKNOWLEDGEMENT

This study was carried out under the Cooperative Research Program of Arid Land Research Center, Tottori University.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). “Crop evapotranspiration.” FAO Irrigation and drainage paper 56, FAO.

Allen, R.G., Trezza, R., Tasumi, M. 2006. Analytical integrated functions for daily solar radiation on slopes. Agricultural and Forest Meteorology. 139:55–73.

ASCE-EWRI. 2005. The ASCE standardized reference evapotranspiration equation. Environmental and Water Resources Institute of the ASCE Standardization of Reference Evapotranspiration Task Committee. American Society of Civil Engineers, Reston, Virginia. 216p.

Duffie. J. A. and Beckman, W. A. 1991. Solar engineering of thermal process. 2nd Ed, John Wiley and sons, NY

Gong, L., Xu, C-Y., Chen, D., Halldin, S., Chen, Y.D. 2006. Sensitivity of the Penman–Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. Journal of Hydrology. 329:620-629.

Hickel, K., Zhang, L. 2006. Estimating the impact of rainfall seasonality on mean annual water balance using a top-down approach. Journal of Hydrology. 331:409-424.

Kannan, N., White, S.M., Worrall, F., Whelan, M.J. 2007. Sensitivity analysis and identification of the best evapotranspiration and runoff options for hydrological modelling in SWAT-2000. Journal of Hydrology. 332:456-466.

Melkonian, J., Riha, S.J., Robin, J., Levine, E. 2007. Comparisons of measured stream flow with drainage and runoff simulated by a soil-vegetation-atmosphere transport model parameterized with GLOBE student data. Journal of Hydrology:333:214-225.

Tasumi, M., Allen, R.G., Trezza, R. 2006. DEM based solar radiation estimation model for hydrological studies. Hydrological Science and Technology. 22:1-4:197-208.

ESTIMATING CROP WATER USE FROM REMOTELY SENSED NDVI, CROP MODELS, AND REFERENCE ET

Thomas J. Trout[1]
Lee F. Johnson[2]

ABSTRACT

Crop water use can be estimated from reference evapotranspiration, ETo, calculated from weather station data, and estimated crop coefficients, Kc. However, because Kc varies with crop growth rate, planting density, and management practices, generic Kc curves often don't match actual crop water use. Recent studies have shown that basal crop coefficients, Kcb, are related to crop light interception or canopy cover; and that canopy cover can be estimated for a wide variety of crops from remotely sensed observations of the normalized difference vegetation index, NDVI. Combined, these relationships could provide good estimates of Kcb from satellite or aerial data for a wide variety of crops over large areas. When combined with ground based ETo measurements and general knowledge of irrigation methods, crop water use can be estimated for individual fields and for large regions. Because NDVI data are generally available only intermittently during the season, simple plant growth models can be used to interpolate canopy cover between vegetation index measurements, and to extrapolate crop canopy cover into the future. This system may improve estimates of crop water use compared to traditional FAO-56 methods and provides an alternative to remotely-sensed estimates of ET that use thermal data with surface energy balance calculations.

BACKGROUND

A common method to estimate crop water use is through use of reference evapotranspiration, ETo, calculated from climatic parameters; and a crop coefficient, based on crop and stage of growth (Allen et al. 1998). Many states in the western U.S. have weather station networks to calculate regional ETo (eg: California Irrigation Management Information Service (CIMIS) http://wwwcimis.water.ca.gov/cimis/welcome.jsp, Colorado Agricultural Meteorological Network (CoAgMet) http://ccc.atmos.colostate.edu/~coagmet/ , and Washington Public Weather System (PAWS) http://index.prosser.wsu.edu/). Several scheduling programs are available to assist users in estimating crop water use from ETo (eg. Waterite http://www.wateright.org/ , KanSched http://www.oznet.ksu.edu/mil/Resources/User%20Guides/KanSchedExcel.pdf and Basic Irrigation Scheduling http://biomet.ucdavis.edu/irrigation_scheduling/bis/BIS.htm).

The weakest link in this weather based approach to predict crop water use and irrigation requirements is the difficulty in reliably estimating the crop coefficient. Crop coefficients are commonly estimated with a relationship based on days since planting, growing degree days, or some aspect of the crop growth stage (Allen et al. 1998, Snyder et al. 2007). A wide variety of irrigated crops are grown under a wide range of conditions, and dependable crop coefficients are

[1] USDA-ARS Water Management Research, 2150 Centre Ave., Ft. Collins, CO 80526. Thomas.trout@ars.usda.gov
[2] Earth Science Div., NASA/ARC 242-4, Moffett Field, CA 94035. ljohnson@arc.nasa.gov

not available for many of the crops and growing conditions. This is especially true for horticultural and other specialty crops that are increasingly important in irrigated areas. These crops are often not well studied and include widely varying varieties grown under a wide range of planting densities and cultural practices.

Crop water use is related to the interception of incoming solar radiation and the amount of transpiring leaf surface. Sunlit leaves transpire at a higher rate than shaded leaves. Both leaf area index (LAI) and crop light interception have been related to crop transpiration. Light interception, as represented either by the portion of the ground surface that is shaded or the crop canopy cover, is much easier to measure than LAI. Although light interception varies with the crop canopy structure and the sun angle, several studies have found that mid-day shading, or equivalently, canopy cover measured vertically, provides a good relative representation of crop transpiration (Johnson et al. 2004, Williams and Ayars 2005, Trout and Gartung 2006, Grattan et al. 1998).

Previous studies have shown that various spectral vegetation indices, calculated from visible and near-infrared reflectance data, are linearly related to the amount of photosynthetically active radiation absorbed by plant canopies (Asrar et al. 1984, Daughtry et al. 1992, Goward and Huemmrich 1992, Maas 2000). Related efforts have specifically addressed spectral estimation of crop coefficients in specific crop systems by ground-based and airborne data collection (Bausch, 1995; Hunsaker et al. 2005; Johnson and Scholasch 2005). Moran et al. (1997) describe the potential and limitations of using satellite imagery for crop management.

Functional relationships between remotely sensed vegetation indices and crop light interception, and light interception and basal crop coefficient, Kcb, allow efficient estimation of crop water use where reference ETo is available. This could allow estimation of crop water use in near real time for individual fields on a regional scale. Such a process was proposed in the DEMETER project in southern Europe (Calera-Belmonte et al. 2003). In this paper, we present preliminary relationships between vegetation indices, light interception, and Kcb developed from data collected in the San Joaquin Valley on horticultural crops, and propose a possible structure for an irrigation scheduling system based on remotely-sensed vegetation indices and ETo.

VEGETATION INDEX vs. CANOPY COVER

On July 1, 2005, and June 19-20, 2006, canopy cover, CC, of 12 high value crops (watermelon, cantaloupe, pepper, bean, tomato, lettuce, onion, garlic, cotton, pistachio, almond, grape) in various stages of growth was measured on 33 fields near Five Points on the west side of the San Joaquin Valley in California. Most fields were drip irrigated and essentially weed free with a dry soil surface. These fields were selected to represent a wide range of major SJV perennial and annual horticultural crops with widely varying canopy cover. Fields were selected that had uniform cropping patterns. Most fields were at least 200 m in the smallest dimension.

Canopy cover was measured with a TetraCam®[3] ADC multispectral camera suspended from a frame directly above the crop and aimed vertically downward. The 1.3 megapixel resolution camera was designed and optimized for capture of red, green and near-infrared wavelengths of reflected light. The photos were analyzed with software (Pixelwrench and Briv32) provided by the camera manufacturer to determine the percentage of the photo area that contained live vegetation.

Landsat 5 Thematic Mapper images of the study area for July 1, 2005 and June 18, 2006 were acquired from the U.S. Geological Survey Landsat Project (http://landsat.usgs.gov/gallery/). On both days there were no clouds over the study area. The study-fields were identified from GPS field coordinates and confirmed with aerial photographs. Landsat digital counts (DC) in the red and near-infrared (NIR) channels were converted to surface reflectance (SR). The reflectance values were then used to calculate per-pixel the normalized difference vegetation index, NDVI (Tucker, 1979) as:

$$NDVI = (SR_{NIR} - SR_{red}) / (SR_{NIR} + SR_{red}) \qquad (1)$$

Landsat processing was performed with ERDAS Imagine 8.7 software (Leica Geosystems). Average NDVI values were calculated for a 7x7 pixel area (approximately 200 x 200 m) within each field. The coefficient of variation for the NDVI values for the 49 pixels was generally less than 10%.

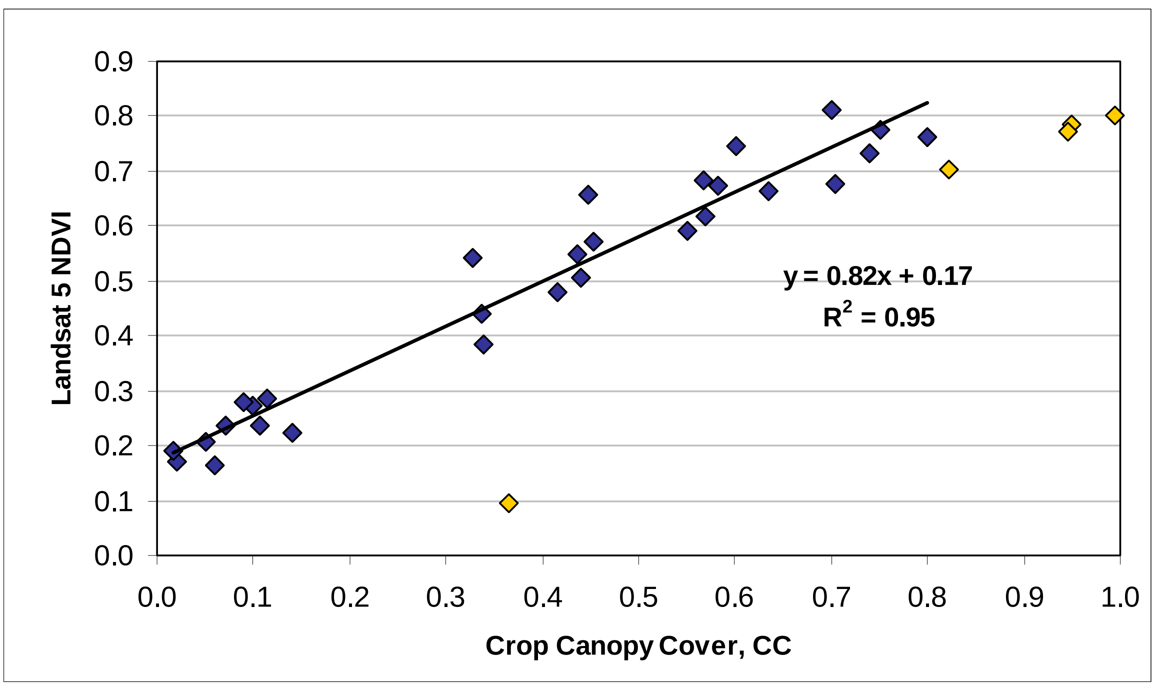


Figure 1. Relationship between Landsat 5 NDVI and Camera Canopy Cover, CC, and the linear regression line for the data represented by blue diamonds.

[3] Reference to specific equipment and brand names are for the benefit of the reader and do not imply endorsement of the product by USDA

Figure 1 shows the correlation between NDVI and CC. NDVI increased linearly with CC to about 0.8, but did not increase further with increasing CC. This finding agrees with past work showing the asymptotic behavior of NDVI at high vegetation biomass (e.g., Tucker, 1979). Thus, data with CC>0.8 were not included in the regression. One field of dark red lettuce had a very low NVDI (= 0.1) in comparison to CC and was excluded as an outlier. The NDVI:CC relationship presented here does not hold for plants with other than green leaves.

For the remaining 28 fields containing 12 different crops, NDVI correlated well with CC (R^2=0.95) (Fig. 1). The intercept value (0.17) represents the NDVI value for bare soil in the area. The soil adjusted vegetation index, SAVI (Huete 1988) was also calculated for the fields, but correlation with CC was no better than with NDVI. These results show that NDVI can be a good indicator of crop canopy cover for a wide range of crops with large differences in canopy structure and cover. The linear relationship is valid up to a CC of 0.8. For most crops, water use does not increase for canopy cover above 0.8 (Doorenbos and Pruitt, 1977; Snyder et al. 2007), so this limitation does not impact estimates of crop water use. Neale et al. (2005) remark that the onset of NDVI saturation corresponds to canopy effective full cover.

We also estimated CC for each field using measurements of canopy widths or crown diameters and estimates of percent shade within the canopy. Our estimates were consistent (R^2 = 0.93) but tended to be about 10% lower than that measured with the camera. This indicates that visual measurements can provide useful estimates when NDVI measurements are not available.

CANOPY COVER vs. BASAL CROP COEFFICIENT

The USDA-ARS Water Management Research Unit in Fresno, CA is using weighing lysimeters to develop crop coefficients for horticultural crops that are grown in the San Joaquin Valley. Past lysimeter research has shown that the basal crop coefficient for grape vines and fruit trees are closely related to mid-day light interception (Johnson et al., 2000, Williams and Ayars, 2005). Current research is determining the relationship between light interception and basal crop coefficient for several major annual SJV vegetable crops. The objective is to develop relationships between light interception, represented by canopy cover, and basal crop coefficient that can be used by growers of horticultural crops. Results from lettuce, bell pepper, and garlic crops were presented by Trout and Gartung (2006) and are summarized here.

Canopy cover was measured several times throughout the growing season by the same camera technique described above. The crop coefficient was calculated as the ratio of the daily crop water use from the lysimeter to ETo (grass reference) measured by the CIMIS weather station #2 (CDWR 2006) located on the adjacent grass field. The crops were sub-surface drip irrigated and only data from days with a dry soil surface were used so that soil surface evaporation was very small and the calculated crop coefficient represented Kcb. Figure 2 shows the daily crop coefficient and measured canopy cover for the bell pepper crop. The early season Kc spikes result from sprinkler irrigations under low plant cover and illustrate the effects of soil surface evaporation. The late Kc decline results from termination of irrigation on day of year 226 and plant stress due to declining soil water content.

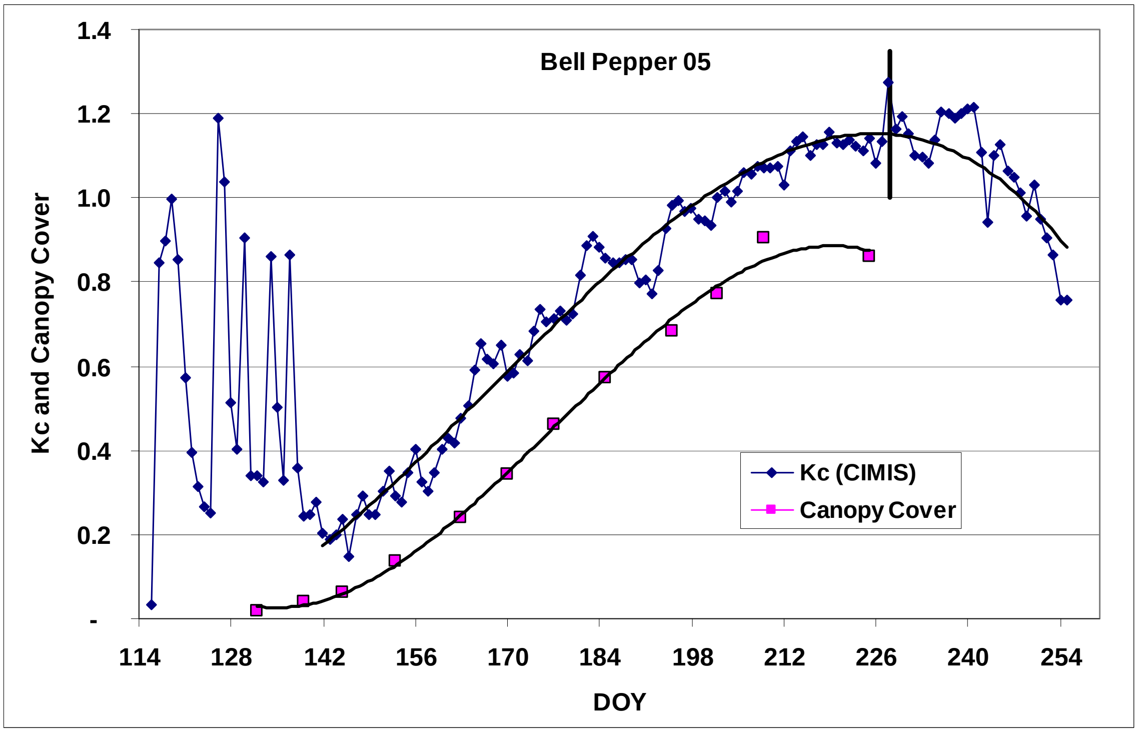


Figure 2. Daily crop coefficient, Kc, and canopy cover for a bell pepper crop grown on a weighing lysimeter on the west side of the San Joaquin Valley, CA in 2005. Peppers were transplanted on day of year (DOY) 115, five sprinkler irrigations were applied before DOY 140, and irrigation was terminated on DOY 226.

Figure 3 shows the relationship between Kcb and CC for the three crops. The lettuce and bell pepper crops, although structurally very different, followed the same linear relationship with an intercept of 0.14 and slope of 1.13 and a very high correlation coefficient. The garlic crop exhibited a higher intercept but smaller slope than the other two crops. The positive intercept is expected because with a sparse canopy during early growth, actual sunlight interception by the crop substantially exceeds vertical light interception and air movement within the canopy is high, resulting in a higher Kcb to CC ratio. As canopy cover increases, most light is intercepted by the top of the canopy and air movement within the canopy is reduced. Once the canopy approaches maximum cover (about 0.9 for these crops), the ratio should approach 1.0 to 1.2, depending on crop height and roughness (Allen et al., 1998). The garlic crop exhibited unexpectedly high Kcb values, possibly due to its upright but fairly dispersed canopy structure.

Figure 4 shows Kc vs. ground cover data presented by Grattan et al. (1998) for seven horticultural crops. These Kc values were determined from ETc measured with Bowen Ratio equipment, ETo from regional CIMIS stations, and ground cover estimated from visual estimates of shaded area (equivalent to CC). Data were collected when the ground surface appeared dry,

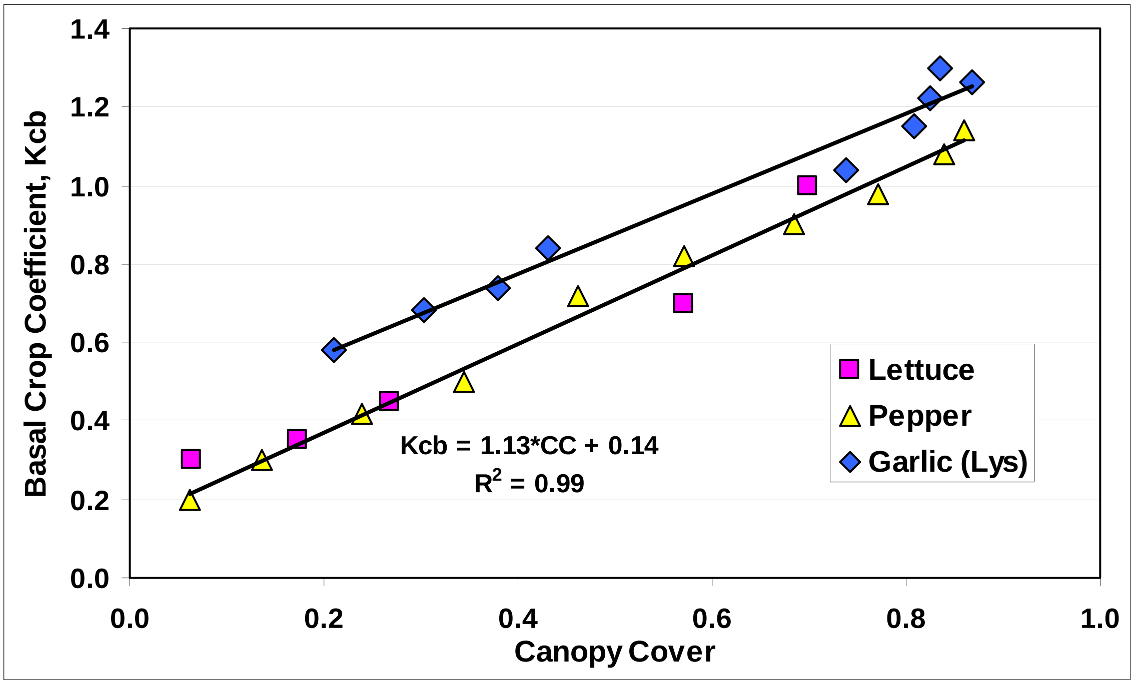


Figure 3. Relationships between basal crop coefficient, Kcb, and canopy cover for three crops grown on a weighing lysimeter on the west side of the San Joaquin Valley, CA. Regression equation is for lettuce and pepper data.

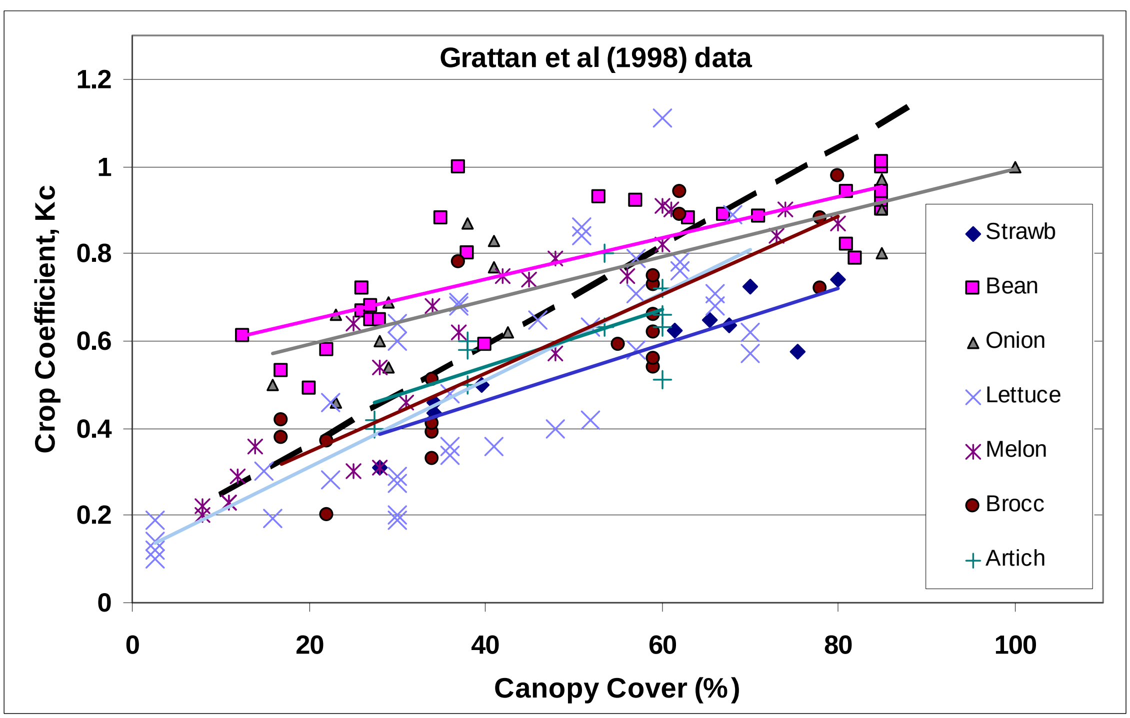


Figure 4. Relationships between crop coefficient, Kc, and canopy cover for 7 crops measured with Bowen Ratio equipment by Grattan et al. (1998). Lines are best fit linear relationships for each crop. Dashed line is lettuce/pepper relationship from Figure 3.

so the crop coefficient should closely approximate Kcb. Although the scatter is large, the Grattan data tends to agree with the lysimeter data (dashed line represents our lettuce/pepper data) fairly well in the low CC range, but is lower than the lysimeter data in the high CC range. Note that the Grattan onion Kc values are higher than for most other crops at low CC (like the garlic in this study), but are not high at high CC values. The high bean Kc values at low CC is unexpected.

ESTIMATION OF FIELD AND REGIONAL CROP WATER USE

The two above relationships can be used to estimate Kcb from remotely sensed reflectance information.

$$CC = 1.22 * NDVI - 0.21 \quad \text{(2) (from Fig 1)}$$

$$Kcb = 1.13 * CC + 0.14 \quad \text{(3) (from Fig 3)}$$

This process should be carried out in two steps rather than attempting to directly link Kcb to NDVI. The intermediate step allows interpolation and extrapolation of CC between and beyond NDVI measurements, ground truthing of CC estimates, and crop specific Kcb:CC relationships.

Imagery to calculate NDVI will only be available at intermittent times, depending on the source, cost, and weather. For example, Landsat photos are available on 16 day intervals. Curve fitting of CC values or simple crop simulation models can be used to fill in between and extend beyond measured values. For a crop that has been studied previously, a generic CC vs. growing degree day (or days since planting) relationship can be developed and then adjusted using NDVI measurements for the current crop. Many crop simulation models output information on plant growth and phenology that can be converted to CC. Measured NDVI estimates of CC can be used to calibrate the models for the current crop and improve model CC projections into the future. When NDVI measurement intervals are long, visual estimates of CC can be used in place of NDVI-based estimates.

The lysimeter measurements presented here (Fig. 3) indicate that the Kcb:CC relationships are highly linear, and may be similar for broad crop types. Current data are inadequate to confidently project Kcb:CC relationships for a wide range of crops. Collecting these basic data should be a priority. Lysimetry is the most accurate way to develop this relationship. Surface energy balance measurements can also be used to estimate crop ET (bowen ratio, eddy correlation, SEBAL) and Kcb. Crop simulation models coupled with atmospheric energy balance relationships may be able to generate Kcb:CC relationships if the models have been adequately calibrated with field data. Allen et al (1998) in chapter 9 presents equations to adjust mid-season Kcb values based on partial ground cover:

$$Kcb' = Kcb - 1 + (fc'/fc)^{0.5} \quad \text{(4) (from Allen et al. (1998), eq. 96)}$$

where Kcb and fc are the midseason basal crop coefficient and ground cover for a “pristine” dense crop and Kcb’ and fc’ are the values for a crop with partial cover. Unfortunately, the authors do not present the fc values that are associated with their Kcb values.

Daily values of Kcb calculated from measured or interpolated CC values can be converted to Kc values by adding the soil evaporation coefficient, Ke. Soil evaporation can be estimated from irrigation schedule and method, canopy cover, soil type, and ETo (Allen et al 1998, chap. 8). Kc is then used with values for ETo from local weather stations, or interpolated ETo maps (Lehner et al. 2006) to estimate total water use for a field.

Information required to estimate crop water use/requirements includes:

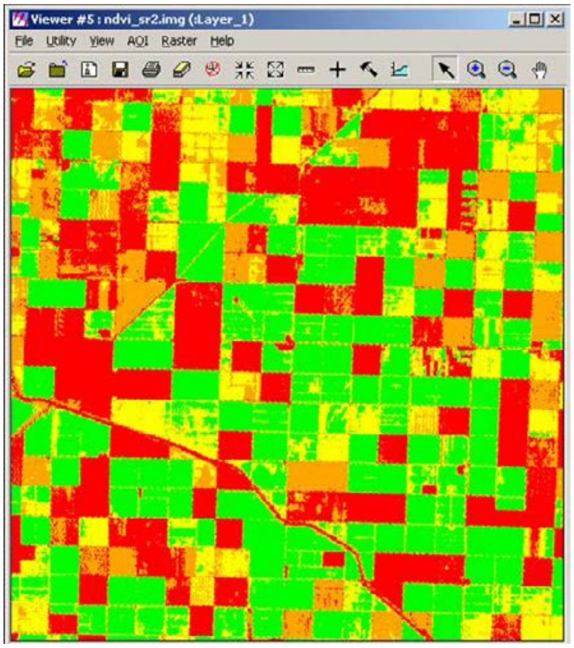
1. Daily canopy cover from NDVI measurements and interpolation models
2. Daily ETo from weather stations
3. Soil type
4. Crop
5. Irrigation method and schedule

The first three items can be generated regionally from satellite or aerial images and ETo and soils databases. The last two can be provided by the farmer or from government or water district surveys. The first, second, and fourth items are required to estimate crop transpiration. The first, second, third, and fifth items are required to estimate soil evaporation, which becomes relatively less important as canopy cover increases. Farmer inputs of crop type, planting date, soil type, and irrigation method are common for irrigation scheduling programs.

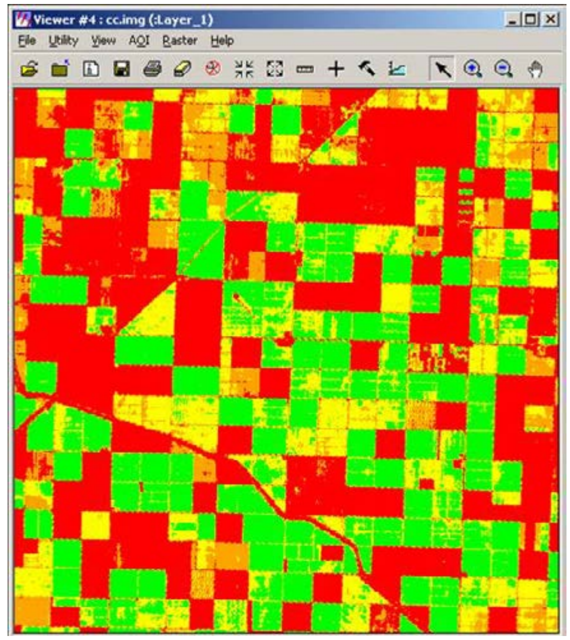
When this method is used to generate regional estimates of crop water use, field-specific crop and irrigation method/schedule information will generally not be available. In this case, regional crop surveys may be used to assign the most appropriate Kcb:CC relationships, and regional irrigation methods/patterns used to estimate soil evaporation losses. Where crop information is altogether lacking, a generic Kcb:CC relationship (e.g., Fig 4) can be assumed.

Figure 5 shows an example of maps of a 200 square kilometer region of San Joaquin Valley fields depicting NDVI, CC, Kcb and crop transpiration values for about 350 fields for July 1, 2005 based on a Landsat 5 image, Eqs. 2 and 3, and a daily ETo for the region on that day of 6 mm. Such aggregated information can be used by water suppliers to estimate water demand for the district or for individual canals.

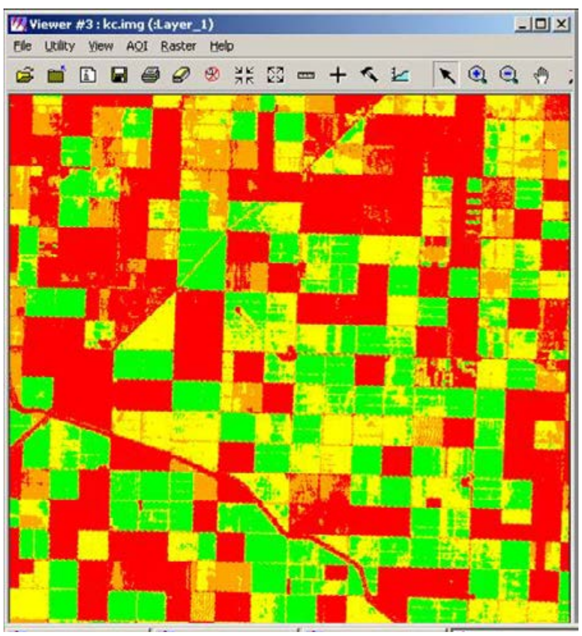
Farmers could use such maps in a GIS framework to identify fields, verify crop canopy cover, and input and store crop and irrigation information for individual fields. The system could then estimate daily crop water use for the field up to the current day, project crop water demand based on historical ETo averages or weather forecasts, and produce maps and tables of cumulative crop water use for a chosen time period. This system would likely be more accurate than current methods, especially for crops grown under conditions other than those used to generate the Kc profile. By virtue of integrative measurements offered by remote sensing, such a system could be more user friendly, and require fewer ground-based measurements, than most current scheduling programs.



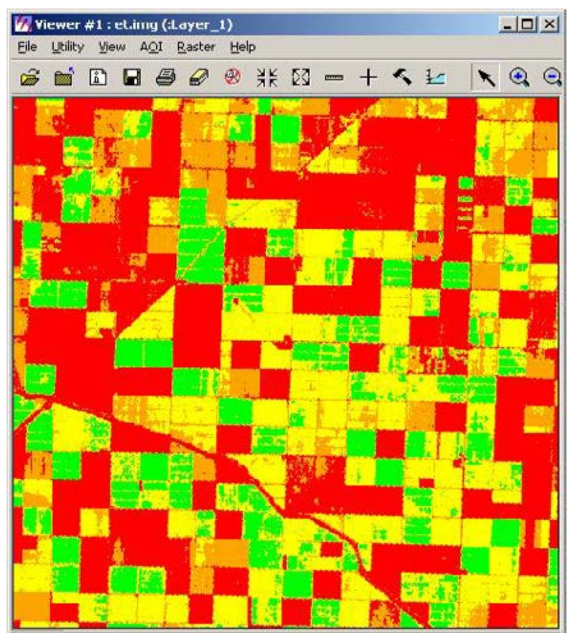
a. NDVI



b. Canopy Cover, CC



c. Kcb



d. Tc

	NDVI, CC	Kcb,	Tc *(mm/day)*
red	<0.2	<0.3	<2
orange	0.2-0.4	0.3-0.6	2-4
yellow	0.4-0.6	0.6-0.9	4-6
green	>0.6	>0.9	>6

Figure 5. Maps of (a) NDVI from a July 1, 2005 Landsat 5 image, (b) Canopy Cover converted from (a) with Eq. 2, (c) Kcb from Eq 3, and (d) Crop Transpiration for the day based on ETo = 6 mm from the regional CIMIS weather station.

REFERENCES

Allen, R.G., L.S. Pereira, D.Raes, and M. Smith. 1998. Crop Evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage paper # 56. FAO, Rome.

Asrar, G., M. Fuchs, E.T. Kanemasu, J.L. Hatfield, 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agron. J. 76:300-306.

Calera-Belmonte, A., A.M Jochum, and A. Cuesta-Garcia. 2003. Space-assisted irrigation management: Towards user-friendly products. ICID Workshop on Remote Sensing of ET for Large Regions. Montpellier, France. Sept 17, 2003.

California Dept. of Water Resouces (CDWR). 2006. California Irrigation Management Information System (CIMIS) WEB site.
http://wwwcimis.water.ca.gov/cimis/infoGenCimisOverview.jsp

Bausch, W.C. 1995. Remote sensing of crop coefficients for improving the irrigation scheduling of corn. Agric. Water Mgmt 27:55-68.

Daughtry, C.S., K.P. Gallo, S.N. Goward, S.D. Prince, and W. P. Kustas. 1992. Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies. Remote Sens. Environ. 39:141-152.

Doorenbos, J., and W.O. Pruitt. 1977. Crop Water Requirements. FAO Irrig. and Drainage Paper #24. FAO, Rome. p. 37.

Goward, S.N. and K.F. Huemmrich, 1992. Vegetation canopy PAR absorptance and NDVI: An assessment using the SAIL model. Remote Sens. Environ. 39:119-140.

Grattan, S.R., W. Bowers, A. Dong, R.L. Snyder, J.J. Carroll, and W. George. 1998. New crop coefficients estimate water use of vegetables, row crops. Calif. Agri. 52:16-21.

Huerte, A.R. 1988. A soil-adjusted vegetation index (SAVI). Remote Sensing of Environment. 25:295-309.

Hunsaker, D.J., E.M. Barnes, T.R. Clarke, G.J. Fitzgerald, and P.J. Pinter, 2005. Cotton irrigation scheduling using remotely sensed and FAO-56 basal crop coefficients. Trans. ASAE. 48:1395-1407.

Johnson, L.F. and T. Scholasch, 2005. Remote sensing of shaded area in vineyards. HortTechnology. 15:859-863.

Johnson, R.S., J. Ayars, T. Trout. 2000. Crop coefficients for mature peach trees are well correlated with mid-day canopy light interception. Acta Horticultura. 537:455-460.

Johnson, R.S., J. Ayars, and T. Hsiao. 2004. Improving a model for prediction peach tree evapotranspiration. Acta Horticultura. 664:341-347.

Lehner, B., G. Umlauf, B. Hamann, and S.Ustin. 2006. Topographic distance functions for interpolation of meteorological data. http://graphics.cs.ucdavis.edu/~hamann/LehnerUmlaufHamannEtAlIRTG_ProceedingsDagstuhlPaper08292006.pdf

Maas, S.J. 2000. Linear mixture modeling approach for estimating cotton canopy ground cover using satellite multispectral imagery. Remote Sens. Environ. 72:304-308.

Moran, M.S., Y. Inoue, and E.M. Barnes. 1997. Opportunities and limitation for image-based remote sensing in precision crop management. Remote Sens. Environ. 61:319-346.

Neale, C., H. Jayanthi, and J. Wright. 2005. Irrigation water management using high resolution airborne remote sensing. Irrigation and Drainage Systems 19:321-336.

Snyder, R.L., M. Orang, S. Matyac, and S. Eching. 2007. Crop Coefficients. http://biomet.ucdavis.edu/evapotranspiration/CropCoef/crop_coefficients.htm

Trout, T.J. and J. Gartung. 2006. Use of crop canopy size to estimate crop coefficient for vegetable crops. Proc. 2006 World Environmental and Water Resources Congress, Omaha, NE., May 2006.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127-150.

Williams, L.E., and J.E. Ayars. 2005. Grapevine water use and crop coefficient are linear functions of shaded area beneath the canopy. Agri. and Forest Met. 132:201-211

ALFALFA PRODUCTION USING SALINE DRAINAGE WATER

Dr. James E. Ayars[1]
Dr. Richard W. Soppe[2]
Dr. Peter Shouse[3]

ABSTRACT

A three year study investigated the use of saline (< 6 dS/m) drainage water for irrigation of salt tolerant alfalfa in the presence of a shallow saline groundwater. The three irrigation treatments included; irrigating with non-saline water, irrigating twice with moderately saline water between cuttings, and irrigating once between cuttings with moderately saline water. Yield data demonstrated that there was approximately a 30% reduction in total yield as a result of using the saline water for irrigation compared to irrigating with the non-saline water. The overall alfalfa quality was improved using saline water. However, there was an accumulation of boron and chloride in the plant tissue with time during each growing season when irrigating with saline water. The boron and chloride values returned to previous levels at the start of the next growing season. There was accumulation of salt in the soil profile and in a shallow groundwater as a result of using saline drainage water for irrigation. A gradual decrease in depth to the shallow groundwater was observed as result of the lack of drainage capability.

INTRODUCTION

Drainage water disposal is limited due to environmental concerns related to high salt content and the presence of trace elements like selenium and boron in drainage water. Reducing the volume of drainage water and salt mass for disposal is a necessary part of a long term solution that will allow irrigated agriculture to maintain its current productivity levels. Reduction of drainage water volume can be obtained through source control (reduction of irrigation application) and/or through the reuse of drainage water (SJVDP, 1990). Applied irrigation water can be reduced when shallow in-situ groundwater is considered a useable water source for the crop (Ayars et al., 2006). Using in-situ groundwater is highly preferable over drainage water reuse since it is more energy efficient for the plants to extract water directly from the source than using pumps to irrigate. The potential of salinization of the root zone exists when saline groundwater moves upward into the soil profile, although earlier research suggests that winter precipitation and pre-plant irrigation are adequate to prevent salt buildup in the root zone (Ayars, 2003). Another option to reduce drainage water volume is to reuse drainage water directly as irrigation water or blend it with fresh water, depending on the quality and composition of the drainage water (Ayars et al., 1993). When salts are added to a field, but do not accumulate in the root zone, it is likely that the shallow groundwater quality is deteriorating. This might not immediately result in higher salinity in the drainage water, however, due to the buffering effect of the groundwater reservoir.

---

[1] Agricultural Engineer, USDA-ARS, 9611 S. Riverbend Ave, Parlier, CA, 93648. jayars@fresno.ars.usda.gov
[2] Engineer, WaterWatch, Generaal Foulkesweg 28, 6703 BS Wageningen, The Netherlands, r.sopppe@waterwatch.nl.
[3] Soil Physicist, USDA-ARS, George E. Brown, Jr. Salinity Laboratory, USDA-ARS, 450 W. Big Springs Rd., Riverside, CA 92507-4617. pshouse@ussl.ars.usda.gov

The concept of shallow groundwater management using subsurface drains has been developed and tested in humid areas, but more research is needed in arid areas under irrigated conditions (Fouss et al., 1990). It has been successful in areas with nearly level ground surface and drainage systems which have closely spaced laterals with shallower depth of placement (< 1.5 m). These are significantly different conditions than normally found in arid irrigated areas.

This paper reports the results of a three-year study that evaluated the potential for using saline drainage water for irrigation of alfalfa in the presence of a controlled drainage system.

MATERIALS AND METHODS

A field was selected in the Broadview Water District (BWD) that had access to both good quality and drainage water. The site was owned and managed by the BWD. The field size was approximately 25 ha and was divided into 9 plots (Fig. 1) each approximately 2.4 ha (90m by 270 m) in size. The 3 irrigation water quality treatments imposed on the site included “FRESH” water, “DRAIN” water, and “GW” groundwater. The site was subdivided into three major blocks, which were further subdivided into three blocks with the irrigation treatments assigned randomly within each of the major blocks. The plots in each block were divided with berms and further subdivided with shallower berms to aid in irrigation.

The “FRESH” treatment used good quality irrigation water and had 2 irrigations of approximately 100 mm each between cuttings. The “DRAIN” treatment used drain water with an EC of approximately 6 dS/m and had 2 irrigations of approximately 100 mm each between cuttings. The last treatment “groundwater” (GW) used drainage water for irrigation and has one irrigation of approximately 100 mm between cuttings. The GW treatment was designed to test whether the alfalfa could use any shallow groundwater in-situ. The original design was to not irrigate the "GW" treatment after establishment and have the alfalfa use only groundwater. This was not feasible because of the high salinity of the ground water eliminated any possibility of in-situ use by the crop.

The characteristics of the soil in the field and the time between cuttings limit the ability to apply more than two irrigations between cuttings. The soil is clay and cracks heavily which slows the advance time and also restricts the total infiltrated depth of water. Each irrigation took approximately 10 days to complete and total of 20 day was needed to complete two irrigations between cuttings. Some time was needed after irrigation for the soil to dry to permit access of machinery to cut the crop.

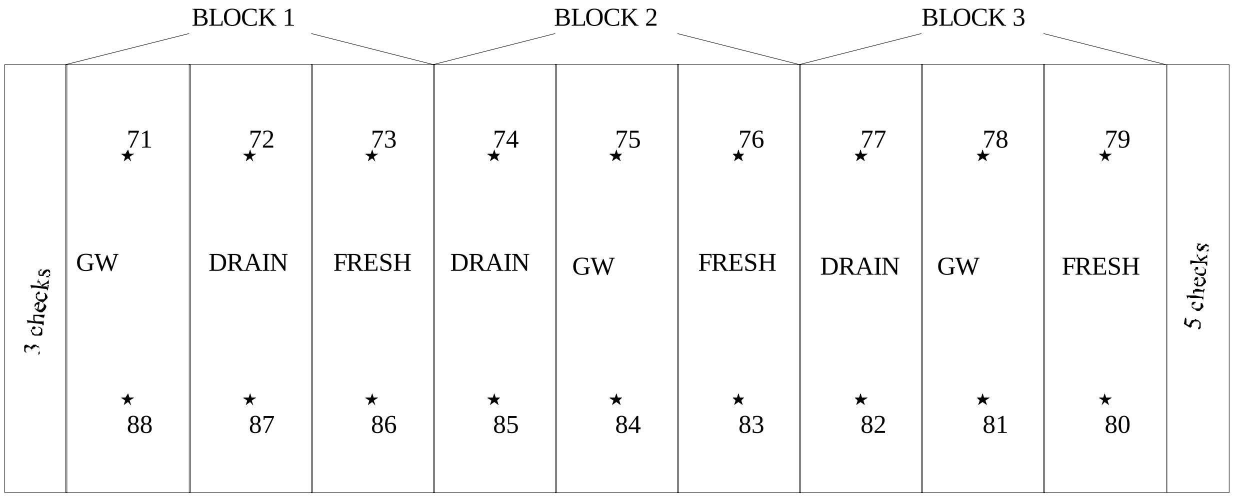


Figure 1. Plot layout for irrigation water quality treatments.

The locations of the groundwater wells used for measuring water table response and collecting ground water samples is shown in Fig. 1 along with the irrigation treatment designation. The sites were labeled from 71 to 88 with two wells in each of the treatment replications. The wells were 2 m deep and were constructed from 50 mm diameter PVC pipe that is perforated over the lower 0.5 m. The water table position in the wells was read either manually and/or with a continuously recording pressure transducer. Some wells were monitored continuously from December 2002 to the end of the project in 2005. All of the wells were sampled periodically for water quality analysis during the duration of the project.

Field Operations:

A safflower crop was grown in 2001 without irrigation to dry down the field in preparation for leveling prior to planting. After harvest of the safflower, the field was disked and laser leveled and prepared for planting of salt tolerant alfalfa in 2002.

Alfalfa (var. SW9720) was planted on February 22, 2002 and was sprinkler irrigated on March 15, 2002 with good quality water to aid in germination. This variety was purported to be more salt tolerant than other varieties being used in the San Joaquin Valley and was selected for this trial. The pertinent values used in the Maas Hoffman equation have not been developed for this variety but it is thought to have a higher threshold value and a steeper yield decline slope. The field was flood irrigated with good quality water beginning on April 18, 2002 and all subsequent irrigations used good quality (low salinity) water until the last irrigation of the season. There were no differential treatments of water quality or numbers of irrigations during the period January to September 2002. The intent was to develop a uniform stand prior to initiating the irrigation water quality treatments. The last irrigation of the season applied drainage water to the ground water (GW) and drainage (DRAIN) treatments.

Irrigation water quality treatments were initiated in the second year of the alfalfa stand (2003). Other field operations were those needed to harvest the crop which included cutting the alfalfa, raking the dried hay into windrows, baling, and then picking up the bales. There were a total of 5 cuttings during the growing season that were spaced roughly 4 to 6 weeks apart. The hay was cut in March, April, June, July, and September. No field operations were conducted from September 2003 to March 2004. Irrigation was applied following the last harvest in 2003 to maintain the alfalfa over the winter dormant period.

The first harvest of the 2004 cropping year was in April and there were a total of 4 harvests during the growing season. All harvest operations were the responsibility of an independent contractor employed by the BWD. Other than harvest there were no other cultural operations done on the plots during the 2004 growing season. The same irrigation protocols were used in 2004 as in 2003.

Soil, Plant, and Water Sampling:

Soil samples were collected by personnel from the George E. Brown Jr. Salinity Laboratory (GEBJSL) between February 28 and March 1, 2001 and were taken to the GEBJSL for analysis of electrical conductivity (EC), and boron (B) and chloride (Cl) concentrations. The site was sampled in the Spring and Fall of each year of the study. The distribution of soil salinity was characterized using the mobile soil mapping equipment developed by the personnel at the George E. Brown Jr. Salinity Laboratory in the Spring of 2003 and 2004. The EM-38 was operated in both horizontal and vertical modes to characterize the apparent salinity distribution in the surface layers and deeper into the profile. The data were tracked with a global position system (GPS) that enabled the data to be plotted on a map that corresponds to other maps being used in the research.

Plant sampling was done prior to harvest at 3 locations in each plot. One location was a random selection in the center third of the field while the other 2 locations were located near the observation wells on each end of the plot and represented the north and south thirds of the field. A total of one square meter of alfalfa was sampled at each location. The samples were dried and ground prior before sending to the laboratory for analysis. A sub-sample of the ground hay was sent to the George Brown Salinity Laboratory for analysis of chemical constituents.

The samples were also sent to a commercial laboratory for analysis using a 30 hour in-vitro analysis recommended by Peter Robinson, Dairy Nutritionist with the University of California at Davis, CA. The data were used to determine the effect of the irrigation treatments and the location of the sample on the quality of the forage. The parameters used in the analysis were: crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), digestible NDF as a percentage NDF (dNDF), non-fibrous carbohydrates (NFC), net energy lactation (Ne_l), fat (EE), ash, in-vitro digestible dry matter (IVDDM).

The groundwater observation wells in test site were sampled periodically starting in the summer of 2002. At the beginning of 2003 the sampling was done approximately monthly until October 2004. The water was analyzed for electrical conductivity (EC), boron (B), and nitrate (NO_3) concentrations. Irrigation water was sampled each irrigation and analyzed for EC.

RESULTS

Water

The CIMIS data for rainfall and the estimated alfalfa water use (Et_c), from the Westland Water District water management guide for the central part of the district were used for comparison with the applied water in the project. The data are summarized in table 1 for the growing season of each year. The total applied water is also given in table 1. The applied irrigation water is further subdivided in table 2 to show the amounts of saline and non-saline water applied each year.

Table 1. Summary of estimated Et_c for well watered irrigated alfalfa and irrigation applications during growing season April-September for 3 years of study.

Year	Rainfall (mm)	ET_c (mm) WWD	Irrigation (mm)		
			FRESH	DRAIN	GW
2002	23	1003	756	700	614
2003	49	808	602	730	474
2004	5.8	990	658	641	641

Table 2. Summary of total applied irrigation water in each treatment for three years of study.

Year	FRESH	DRAIN		GW	
	NS (mm)	NS (mm)	S (mm)	NS (mm)	S (mm)
2002	805	546	202	546	117
2003	602	109	621	109	365
2004	658	315	326	315	326
Total	2216	970	1390	970	903

NS - non-saline, low salinity (0.5dS/m)
S - saline, (3 - 6 dS/m)

The total irrigation was approximately 60 to 70% of the crop water requirement for a well watered alfalfa crop estimated using the Westlands guide. This was a result of the irrigation system design and management and the soil type as previously discussed. Saline water made up nearly 50% of the total water requirement. To determine the impact of this amount of saline water on soil salinity, the average volume weighted salinity was calculated for each treatment for each year of the experiment using measured salinities and applied water along with rainfall. This calculation included the total amount of rainfall during the year, since there is the potential for leaching as a result of rainfall. The results of this calculation are summarized in table 3.

Table 3. Volume weighted average electrical conductivity of irrigation water for irrigation treatments.

Year	FRESH (dS/m)	DRAIN (dS/m)	GW (dS/m)
2002	0.52	1.96	1.44
2003	0.40	5.68	5.28
2004	0.58	3.23	3.23

These values were used along with the applied water in each year to determine the salt load being applied to treatment.

Groundwater Response

In Fig. 2 two wells in the FRESH water treatment were used to demonstrate the response of the shallow groundwater to irrigation and to managing the ground water by turning off the drain system sump pump. Well 73 is located on the west side of the field adjacent to the district water supply canal and well 80 is located on the east side of the field. The drainage system laterals discharge on the west side of the field. The water table depth data for other wells in the FRESH treatment plots were located between these two wells. The data demonstrate a gradual decrease in the depth to the water table with time over the irrigation season and an increase over the winter. This pattern is repeated each year of the project and in all treatments. The deepest water table depth was found on the east side of the field. The initial depth was not greater than 2 m which does not limit crop use from shallow groundwater with a fluctuating water table, particularly with a deep-rooted crop like alfalfa. The average depth to the water table decreased over the duration of the project since the drainage sump was not operated after 2003.

Salt Balance

The sustainability of a reuse system will depend on the salt management within the soil profile and the accumulation in the ground water. The “salt balance” is a concept that is used to quantify the salt management within an agricultural area and the definition is that as much salt should leave the area as comes into it. This will ensure no accumulation of salt and should sustain the production system. This approach to salt management is no longer possible in the BWD on the westside of the San Joaquin Valley because of limitations on drainage water disposal. Instead, the approach will be to manage salt in the crop root zone to limit the accumulation to levels that are not injurious to crop production. Salt in the root zone will have to be moved out of the root zone and lower into to the soil profile or into the ground water. This suggests that there will be finite life span for a field and that there will be a progression of cropping as the soil becomes progressively more saline.

The applied irrigation water data were combined with the weighted average salinity data to calculate the salt load applied to each of the irrigation treatments. These data are summarized in Table 4. A total of 7 Mg/ha were applied to the plots in the FRESH treatment while a total of 53 Mg/ha was applied to the DRAIN treatment and 33 Mg/ha to the GW plots. The additional irrigation in the DRAIN plots accounted for the increased salt load.

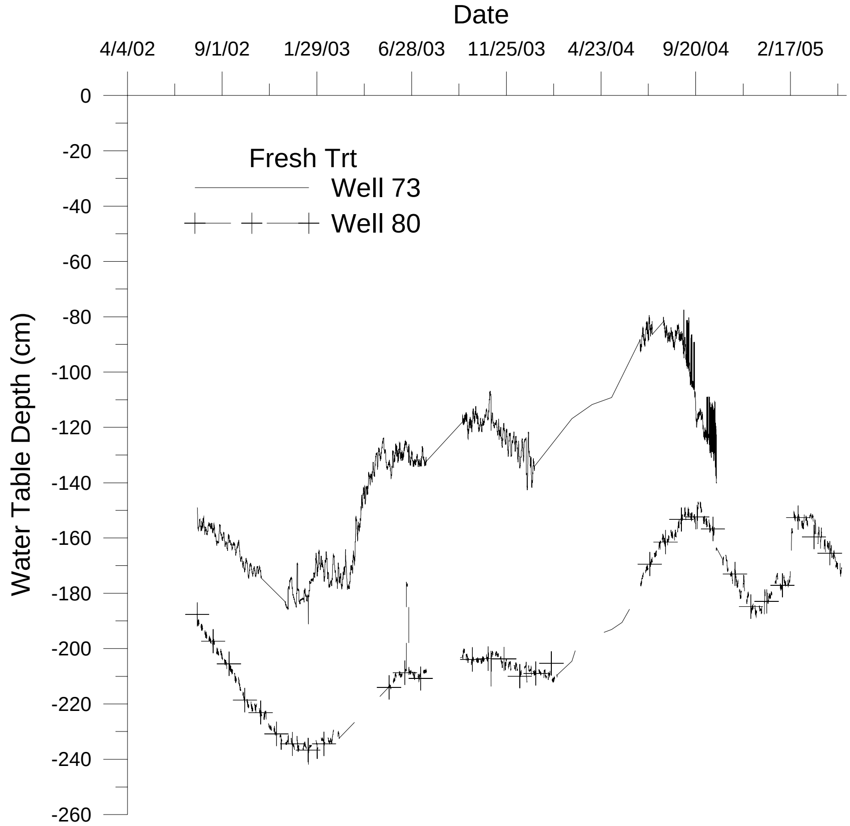


Figure 2. Water table response in groundwater wells in "FRESH" irrigation treatment.

Table 4. Summary of salt load applied from 2002 to 2004.

	FRESH	DRAIN		GW	
Year	NS (Mg/ha)	NS (Mg/ha)	S (Mg/ha)	NS (Mg/ha)	S (Mg/ha)
2002	2.7	1.5	78	1.5	4.5
2003	1.9	0.3	35.0	0.3	19.0
2004	2.4	0.6	9.9	0.6	9.5
Total	7.0	2.4	52.7	2.4	33.0

The groundwater EC data were averaged by sample date and have been plotted in Fig 3. for the GW, DRAIN, and FRESH treatments. These data demonstrate a distinct pattern of increasing concentration during the irrigation season followed by a decrease over the winter months with an increase in the next irrigation season The highest salinity is in the DRAIN treatment that was irrigated twice between harvests with saline drainage water. The intermediate value is under the FRESH treatment which was irrigated twice between harvests with low salinity water. The lowest average salinity is under the GW treatment that was irrigated once between harvests with saline water. There is considerable variability in the data so there is probably no statistical difference between the two curves.

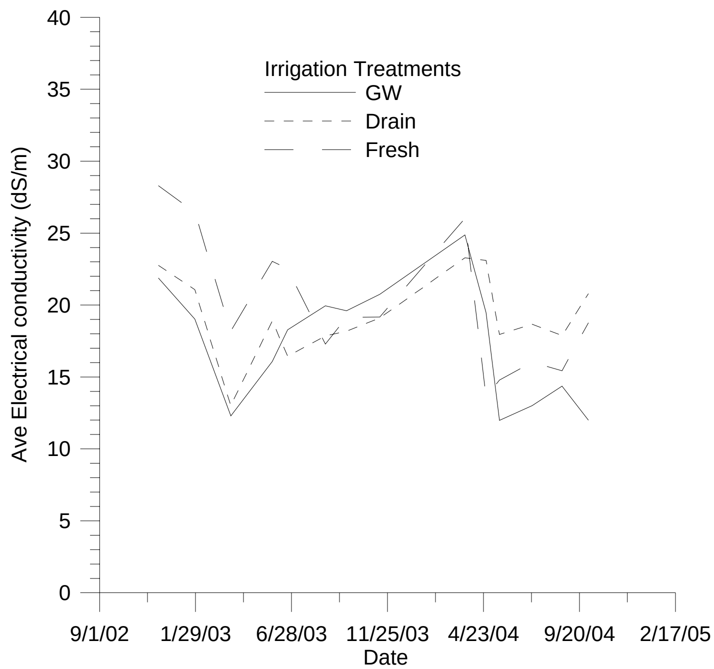


Figure 3. Average electrical conductivity of shallow groundwater under FRESH, DRAIN, and GW irrigation treatments.

The boron data in the shallow groundwater were averaged over the same time period and in the same manner as the EC data. These data are given in Fig. 4 and there is the same pattern of increasing and decreasing concentrations as demonstrated in the EC data.

EM-38 Analysis

The data from surveys with the EM-38 are mapped in figure 5a and 5b for 2003 and 6a and 6b for 2004. The scales were maintained from year to year but there are some differences in the color coding associated with the scales for subsequent years. It is important to realize that the data are averaged over depth and are good for indicating patterns of accumulation but don't provide data for specific depths.

The data show there was a progressive accumulation of salt when saline water was applied compared to fresh water. There is also a difference between the DRAIN and GW treatment. In this case the DRAIN treatment received two irrigations between harvests and the groundwater treatment only received one. This resulted in the drainage treatment becoming more saline than the groundwater treatment. The soil lowest salinity was found in the FRESH treatment as would be expected since only minor amounts of salt had been added during irrigation compared to the other two treatments. The vertical measurements were more saline than the horizontal treatments for a given treatment demonstrating the increased soil salinity with depth. The data show a progressive increase in the soil salinity over the 3 years of the study as a result of the application of irrigation water with limited opportunities for leaching.

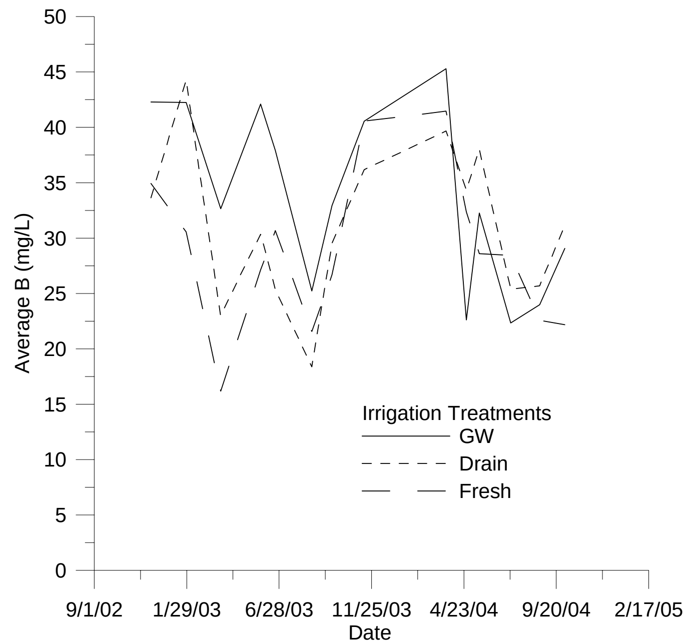


Figure 4. Average boron concentration in the shallow groundwater under the GW, FRESH and DRAIN irrigation treatments.

Plant Analysis

The total bale counts for each irrigation treatment by year are summarized in Table 5. Only the two years when the irrigation treatments were imposed are given. There was approximately a 30% drop in yield in the plots receiving saline water compared to the FRESH treatment. In each year the largest component of the yield was in the first cutting following dormancy with the yield getting progressively smaller with each cutting (data not shown). Bales weighed approximately 68 kg.

Table 5. Bale summary for Broadview plots for 2003 and 2004.

Year	FRESH		DRAIN		GW	
	Bales	Mg/ha/mm	Bales	Mg/ha/mm	Bales	Mg/ha/mm
2003	880	.038	716	.026	707	.038
2004	625	.027	331	.015	427	.019
Total	1505		1047		1134	

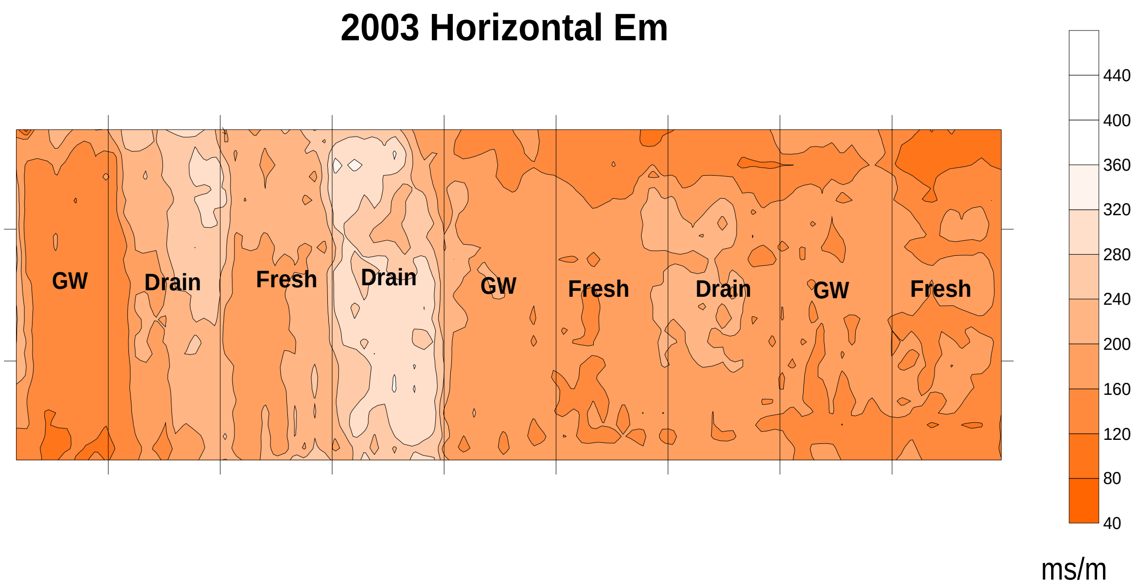


Figure 5a. Apparent soil electrical conductivity measured with EM-38 in horizontal mode in the spring 2003 on field 33 of the Broadview Water District

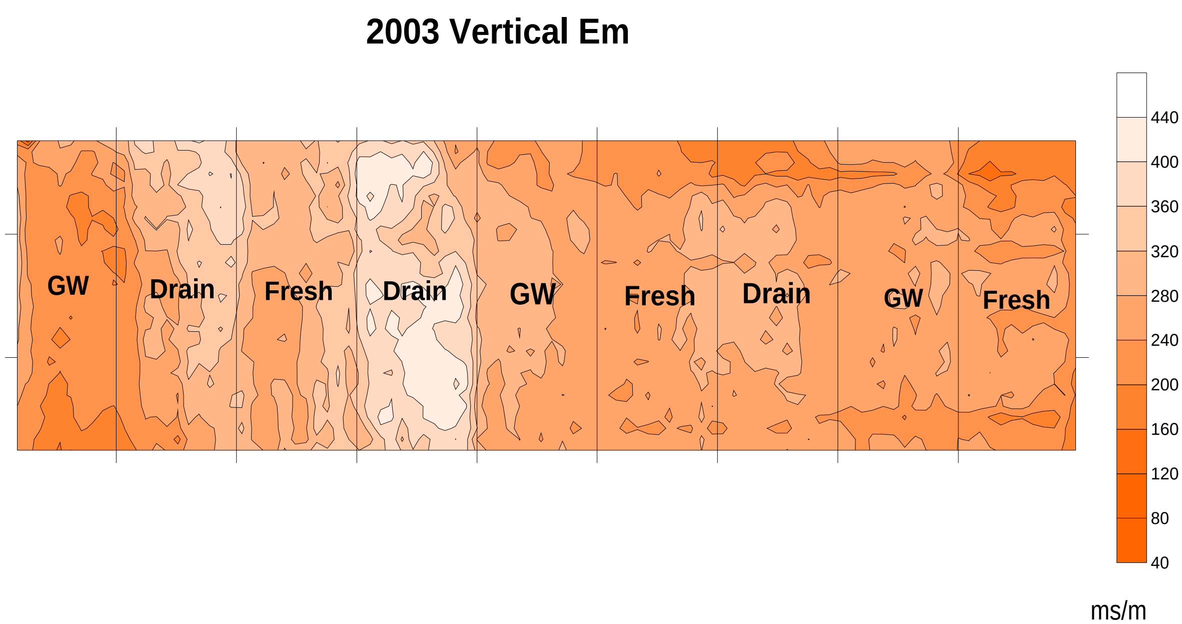


Figure 5b. Apparent soil electrical conductivity measured with EM-38 in the vertical mode in the spring 2003 on field 33 of the Broadview Water District.

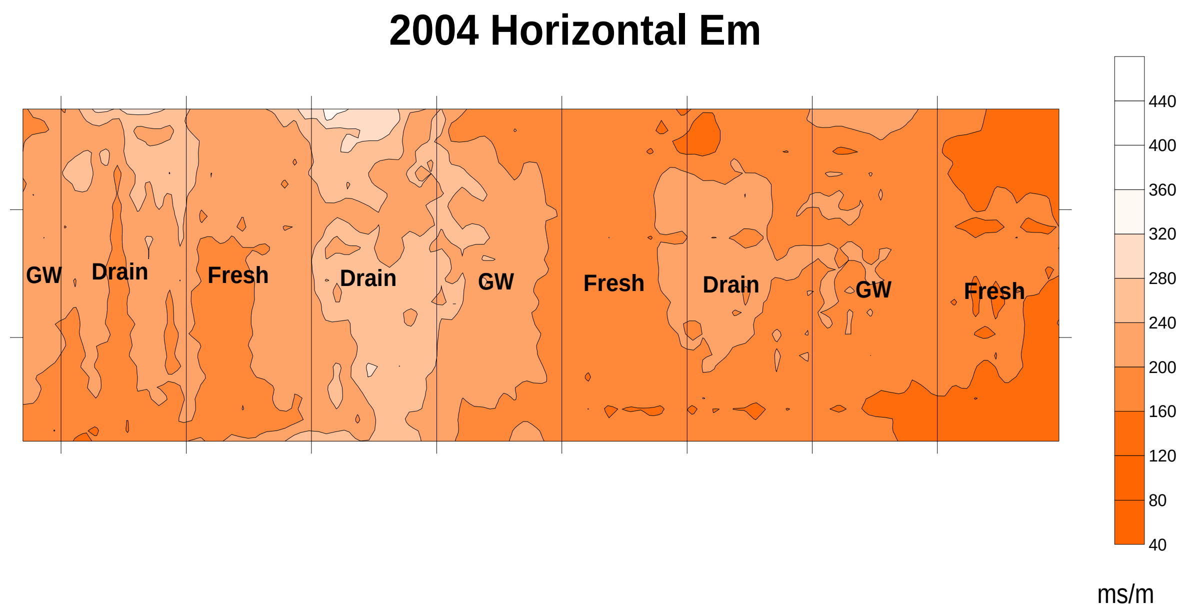


Figure 6a. Apparent soil electrical conductivity measured with EM-38 in horizontal mode in the spring 2004 on field 33 of the Broadview Water District.

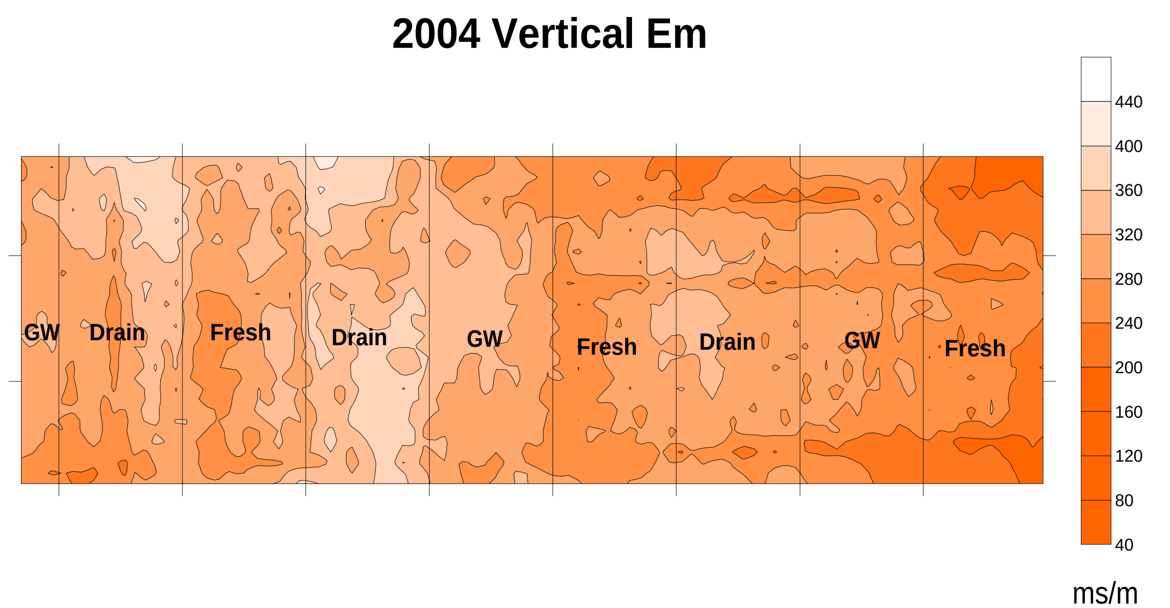


Figure 6b. Apparent soil electrical conductivity measured with EM-38 in the vertical mode in the spring 2004 on field 33 of the Broadview Water District.

In 2003 there were statistical differences by treatment in the quality parameters NDF, NFC, and EE as well as in the yield (data not shown). The highest yield values were found in the FRESH treatment. In the second cut of 2003 differences were noted by location in the field between the north, center, and south. There were differences in yield both by treatment and location. Fresh had the highest yield and the south location was highest. By cut 3 differences were found in all forage quality parameters as a function of water quality treatment. Yields were significantly different by location in the field for all treatments. In cut 4 there were statistical variations by treatment and well as the CP. The irrigation was applied from the south side of the field and as a result there is more water infiltrated on the south side than on the north side (tail end) of the field

In 2004 there were no differences in yield in cut 1. In the forage quality parameters there were differences in the ADF and the NFC by treatment and differences in EE by location. In cut 2 statistical differences developed in the ADF, NDF, dNDF, NFC, IVDDM by treatment. In cut 3 the CP was different by location and treatment. There were significant yield differences by treatment. These data demonstrated that there were significant effects on yield and quality relative to the quality of applied water and total applied water.

The water productivity is also given in table 5. Using an average bale weight of 68 kg, the yields were converted to an average on a hectare basis and divided by the applied water and rainfall sum as given in table 1. It is interesting that the productivity in the GW treatment in 2003 was similar to the FRESH treatment that year. The productivity was reduced in subsequent years with the use of saline water for irrigation.

Since the plants are being grown in saline soils and irrigated with poor quality water there is a need to consider the accumulation of various ions in the plant material. The Cl and B concentrations were averaged for each treatment and plotted in Fig 7 and 8, respectively. The data show in 2003 and 2004 that the concentration in plant was related to the total applied drainage water. The concentration increased from FRESH to GW to DRAIN. This is not the case in 2004

DISCUSSION

The utility of a reuse system relies on the ability of the manger to dispose of saline water in a manner that maintains production and minimizes environmental impact and is hopefully cost effective. Over the course of this study there was approximately 1390 mm of saline water applied to the drainage treatment and 903 mm applied to the GW treatment. There was no drainage from the site and there was a gradual decrease in the depth to the shallow ground water. The estimated crop water use in 2003 was 602 mm for Fresh, 730 mm for Drain, and 474 mm for the GW treatment. In 2004 the crop water use was 658 for the FRESH and 641 for the DRAIN and GW. The differences in applied water probably account for the change in water table depth.

Crops respond to the average irrigation water salinity over the season. The weighted averages for the individual treatments are summarized in Table 3. In 2003 the EC exceeded the Maas-Hoffman threshold salinity for alfalfa and some yield loss would be expected in the DRAIN and GW treatments. The yield decreased through the growing season as the salinity values increased. The yield data taken for sampling for forage analysis also demonstrated the need to manage the distribution across the field. The yield loss was highest on the tail end of the field which received the smallest amount of water. The yield response from season to season demonstrated the need to use low salinity water over the winter for some reclamation of the soil. This would not be needed in a situation with lower salinity water being a part of the reuse system. The water productivity decreased in 2004 as a result of using saline water for irrigation.

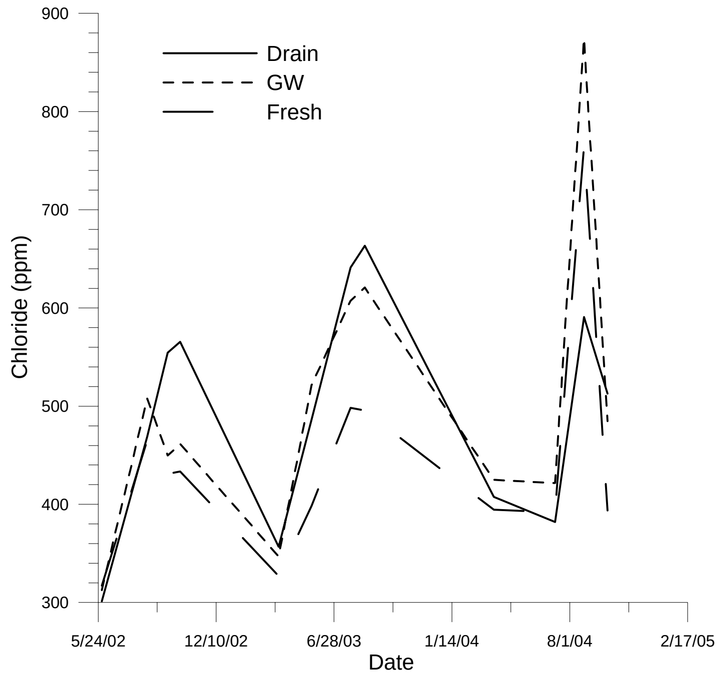


Figure 7. Average chloride concentration in alfalfa for each irrigation treatment.

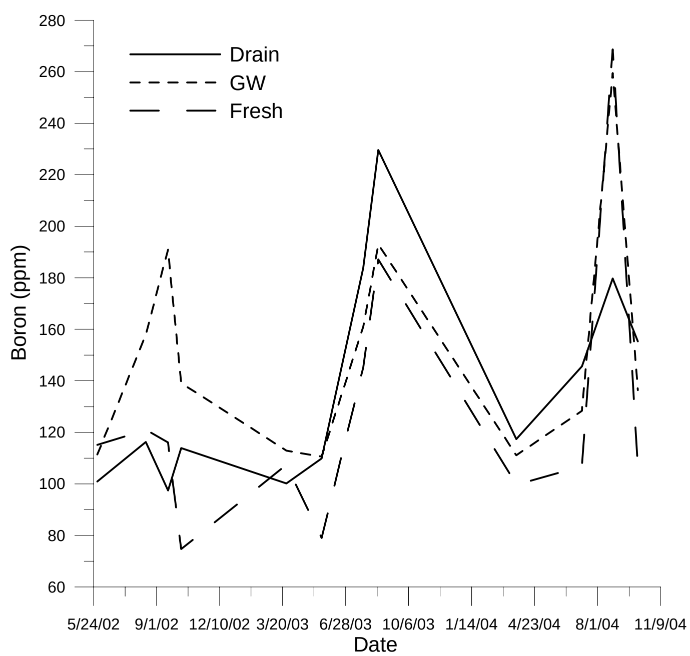


Figure 8. Average boron concentration in alfalfa for each irrigation treatment.

The quality of the forage is also a critical consideration of the system. The data for the parameters that describe the forage quality show that the alfalfa quality was improved as a result of irrigation with saline water. The stress induced by the salinity reduced the forage mass but increased the NEL. Use the values for CP and NDF and ADF the alfalfa generally was graded as premium or better which would result in good price for the alfalfa. The B and Cl concentrations increased with time during the season but reduced to previous levels at the beginning of the next season so these parameters should not be a problem.

There was a gradual increase in the average soil salinity with time as a result of the lack of drainage water disposal capability. For this site to be viable some offsite drainage water disposal will be required. There were distinct differences in the salinity response in the two treatments being irrigated with saline water. The DRAIN treatment was accumulating salt faster than the GW treatment and the EC of the ground water reflected the additional salt loading as did the soil salinity.

CONCLUSIONS

The salt tolerant alfalfa used in this study has potential for a reuse system but will be most effective with lower salinity water.

Drainage from the site is needed to maintain soil salinity at acceptable levels.

A reuse system will require a well managed irrigation system. Surface systems can be used but will require either larger flows or shorter run lengths to minimize distribution non-uniformity.

Yields can be maintained by increasing the irrigation frequency compared to the system being used and periodic use of lower salinity water to maintain the average soil salinity. The soil salinity should be lowest when alfalfa breaks dormancy in the spring.

EM-38 can be used to manage the salinity levels and characterize the accumulation of salt.

REFERENCES

Ayars, J.E. 2003. Field crop production in areas with saline soils and shallow saline groundwater in the San Joaquin Valley of California. Journal of Crop Production 7:353-386.

Ayars, J.E., E.W. Christen, R.W.O. Soppe, and W.S. Meyer. 2006. Resource potential of shallow groundwater for crop water use-A review Irrigation science 24: 147 -160.

Ayars, J.E., R.B. Hutmacher, R.A. Schoneman, S.S. Vail, and T. Pflaum. 1993. Long Term Use of Saline Water For Irrigation. Irrigation Science 14:27-34.

Ayars, J.E. and R.W. Soppe, 2001. *A three-year active land management program to reduce drain water and improve wildlife habitat. Final report*. USDA-ARS-Water Management Research Laboratory, Fresno, CA.

Fouss, J.L., R.W. Skaggs, J.E. Ayars and H.W. Belcher, 1990. Water table control and shallow groundwater utilization. In: *Management of Farm Irrigation Systems*. Eds. G.J. Hoffman, T.A. Howell and K.H. Solomon. American Society of Agricultural Engineers, St. Joseph, Michigan, 783-824.

San Joaquin Valley Drainage Program, 1990. *A management plan for agricultural subsurface drainage and related problems on the westside of the San Joaquin Valley*. Eds. U.S. Department of the Interior, California Resources Agency. California Department of Water Resources, Sacramento, Ca. 183 pg.

PERFORMANCE EVALUATION OF SUBSURFACE DRAINAGE SYSTEM UNDER UNSTEADY STATE FLOW CONDITIONS IN COASTAL SALINE SOILS OF ANDHRAPRADESH, INDIA

S. Ramesh Chandra[1]
K. Shyamsundar [2]

ABSTRACT

The performance of an executed subsurface drainage system was evaluated under unsteady flow conditions. The impulse-response relation has been studied for two different conditions of drain spacings, namely, the executed drain spacing based on steady state flow conditions and the drain spacing proposed on unsteady state flow conditions, incorporating the effects of drainable porosity. It is found rational to use the "Dezeeuw-Hellinga model" for prediction of impulse response relations in terms of temporal water table fluctuations against rainfall – recharge under unsteady state flow conditions. The responses of a sub-surface drainage system for the impulse of incessant rainfall have been studied. The values of calculated drain spacings varied from 11 to 15 m. However, due to economic conditions, the practical drain spacings of the layout have been fixed at wider value of 35m and 55m. It is found that the drain spacings adopted for unsteady state flow conditions might have resulted in a better performance of the drains compared to steady state drain spacing as depicted by Dezeeuw-Hellinga model run. The drainable porosity being the vital parameter in an unsteady state equation, the Dezeeuw-Hellinga model was also used for varying levels of drainable porosity under given drain spacing conditions. Generally, the reference drainable porosity value is taken as 10 per cent for most of the drainage studies and the influence on drain outflows were compared for an increased value of 20 per cent and decreased value of 5 per cent, since the drainable porosity value in the study area varied from 5 to 20 per cent. It was found that the change in drainable porosity significantly influence the drain performance as depicted by Dezeeuw-Hellinga model run over all the3 standard week of year. The executed sub-surface drainage system has been found satisfactory in bringing down the soil salinity levels to desirable limits below 4 dSm^{-1}. The executed sub-surface drainage system has also resulted in appreciable crop productivity improvements in the locality.

INTRODUCTION

Chemical degradation of agricultural land some times is a result of faulty irrigation water management besides being an inherent problem in several parts of the country. Such degradation may manifest in salinity, sodicity, avidity and a toxic environment in the crop root zone. The result is a reduction or loss of production. Besides chemical degradation, large areas in the country suffer from water congestion due to high rainfall, flat topography, poor water transmission characteristics in the soil profile and lack of natural or artificial drainage.

---

[1] Formerly, Scientist (SWE) I and Head, AICRP on Agril. Drainage, Machilipatnam and presently working as Scientist SG(Agril. Engg.), AP Water Management project, Bapatla 522101.A.P, INDIA
[2] Formerly, Scientist (Agronomy), AICRP on Agril. Drainage, Machilipatnam and presently working as Scientist (Agronomy), Rice research unit, Agril. College Farm, Bapatla. 522101.A.P, INDIA

Land degradation caused by water logging and soil salinity problems adversely affect the food security and living standards of human beings. The history of irrigation projects in recent times shows that the problems of water logging, salinity and alkalinity are rising even before the full potential of the projects are realized. As a result, much of the investment is irrecoverably wasted. Land drainage plays an important role in maintaining and improving crop yields in problematic soils by way of managing groundwater tables and soil salinity at safer levels.

As sub surface drainage system continuously removes dissolved salts from soil profile, it is apprehended that some amount of various species of water-soluble nitrogen namely, ammonium nitrite and nitrite may also be lost through sub surface drainage water. Thus, it was has chosen to review and comment on some of the studies related water table and salinity control by sub surface drainage in chemically degraded lands. The findings of such studies were based on modeling as well as experimental approaches to assess desalinization in the presence of sub surface drainage; salinization in the absence of adequate drainage; water quality monitoring of drainage effluents; soil salinity distribution in space and time; nitrogen losses *viz* leaching and sub surface drainage effluents. The provision of sub surface drainage would help in reclamation of water logged saline soils in a few years and a wide choice of crops can be grown to achieve full potential of the area. Sub surface drainage designs are now considering the controlled drainage to eliminate some of the negative effects such as over drainage, fertilizer losses and environmental problems. Sub surface drainage research in India has shown a number of positive impacts such as salinity reclamation in 2 to 4 years, increase cropping intensity, advancing of soil trafficability period by 5 to 10 days, increased crop yield by 40-50 per cent, improvement in the quality of produce, increased land value and a better social environment.

MATERIALS AND METHODS

To accomplish the objectives of any drainage scheme, a sound hydraulic design of the system with particular reference to the drain spacing and an appropriate technique to evaluate the performance of the system after layout is essential. A through study of soil characteristics, rainfall pattern and water table fluctuations is warranted towards the design and layout of drainage system. The experimental site is located at the Endakuduru village in Ghantasala Mandal of Krishna District in Andhra Pradesh as shown in Fig: 2.1. The village is located on the Machilipatinam- Challapelli road at a distance of about 18 km southwards from the district head quarter, Machilipatinam. Krishna district lies in south coastal Andhra Pradesh between $15^0 43^1$ and $17^0 10^1$ N latitude and $80^0 0^1$ and $81^0 35^1$ E longitude extending over an area of 8727 Sq. km. with a costal line of 88 km. Majority of the people of the study area are marginal farmers with an average land holding of 0.61 ha. These marginal farmers are generally poor and earn their livelihood by working as labourers to big farmers.

The district occupies an important place in agriculture and rice in the main food crop occupying about 58 per cent of the gross cropped area of 7.59 lakh hectares. The other crops are black grams, green grams, ground nut and sugarcane grown in 1.29, 0.36, 0.29 and 0.17 lakh hectare, respectively. The gross irrigated area is about 63 per cent of the gross cropped area. The experimental site is characterized by a moderate coastal climate throughout the year. the mean annual maximum and minimum temperatures are 36.6^oC and 19.3^oC respectively. The mean annual rainfall is 975 mm of which about 60 percent occurs during south-west monsoon from June to September. A specific feature of the area is occurrence of cyclonic storms, any time usually during September to November, causing torrential rains. The rainfall during September to November may be as high as 40 to 45 percent of the annual rainfall. Endakuduru village and the experimental fields are 1.5 to 2 m above the mean sea level. The land flat and is diked in small units for rice cultivation. It is saline to sodic with high clay content. The soil is deep with no rock formation.

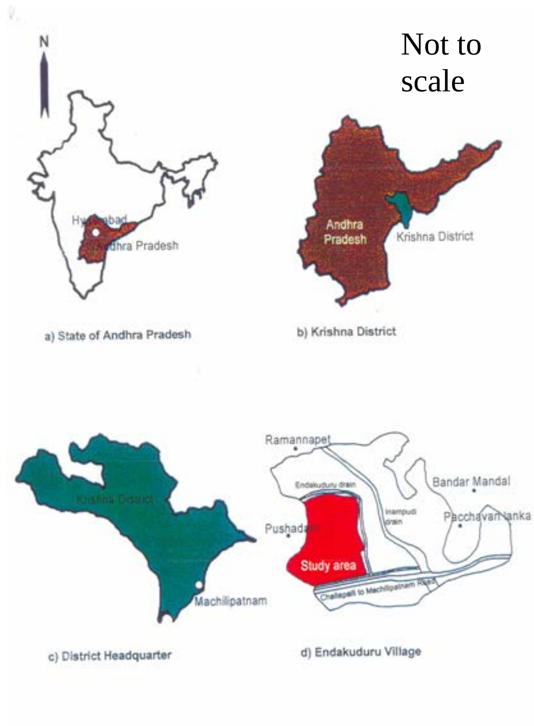


Figure 1. Successive maps of the study area

The soil at the project state, in general, is saline in nature with varying degrees of salinity. The soils with low levels of salinity (EC values less than 4 dS/m) are kept under cultivation with rice-rice rotation. Soils with high salinity content are barren and nothing grows on it with white crust formation on the surface. It is noticed that the project site soils have poor permeability characteristics. The salts are crusted on the surface especially during hotter months with white salt patches on the land surface slightly alkaline in nature i.e., $p^H > 7.00$. The soils deep with no rock formation. Sandy layer is observed at depths more than 2 metres. Normally rice-rice cropping system is followed in Endakuduru village. During *kharif*, rice varieties of about 150-160 days duration and during *rabi*, rice varieties of about 120 days duration are grown. As the village is located at the tail end of the irrigation canal system, the rice transplantation is generally delayed and is done any time between mid-July to mid-August. As a result of delayed showing the yields are reduced by about 10-15 per cent. The area is affected by salt content and drain water is used for protective irrigation for the rice crop. The crop yield in *kharif* is lower compared to *rabi* yield because of less sun light conditions. The rice varieties Chaitanya (MTU-2067), Krishnaveni (MTU-2077) and Swarna usually grown in *kharif* season and the rice variety

IR-64 is cultivated in *rabi* season. However, these yields can be increased by about 20 per cent if proper drainage practices are employed.

RESULTS AND DISCUSSION

As shown in Figure 2, the basic factors that decide the drainage coefficient are hydraulic conductivity, infiltration rate/ percolation, leaching requirement and available water to accomplish leaching. As a preliminary guideline towards design, the least of the above factors will be the deciding parameter for adoption as drainage coefficient. Of the above, the 'K' and the infiltration rate have been found to be 0.144 m/day to 0.028 m/day respectively. Either of the two is very high to be considered as drainage coefficient. As an amount towards finding the leaching requirement, a simple water balance approach was studied.

First, the 20-year monthly rainfalls were arranged in a descending order table for each of the 12 months. The 75 percent probable value of monthly rainfalls at 75 percent probability level of being equaled or exceeded have been plotted. The cumulative monthly evapotranspiration was also plotted in the same graph. The maximum deficit of rainfall was found in December and its magnitude was 1150 mm.

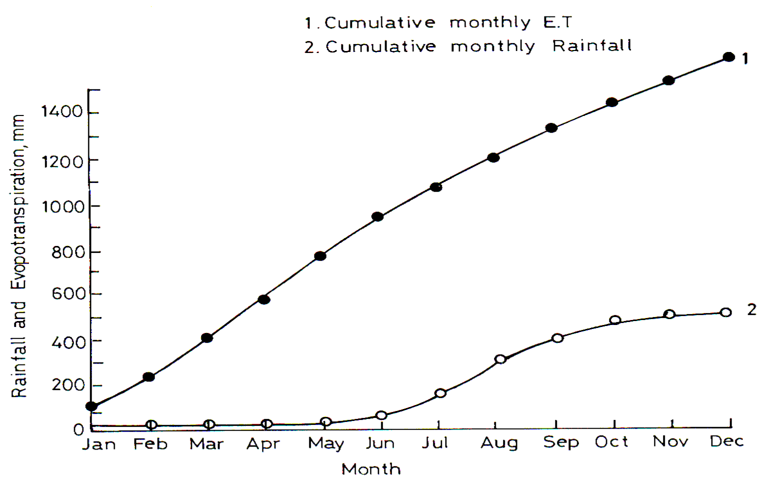


Figure 2. Simple water balance of study area

Leaching requirement is given by the formula:

$$LR \;=\; (E-P) \;\times\; \frac{\overline{C_i}}{F(\overline{C_{FC}}-\overline{C_i})} \qquad (1)$$

Where,

LR = Leaching requirements, mm
E = evapotranspiration, mm
P = effective rainfall, mm
C_i = average irrigation water salt concentration, ml/l
C_{FC} = average salt concentration of soil at field capacity, me/l and

F = leaching efficiency

of the various components of equation, (E-P) was obtained from Fig. was taken as 0.4 for heavy soils, C_i and C_{FC} were worked out from the field measured data of the electrical conductivity during investigations by using the following general relations.

Concentration in me/l = 12 x concentration in dS /m
Concentration at field capacity = 2 x concentration of 1:2 saturation extract
For the present study:

E-P = 1150 mm
F = 0.4 (assumed for heavy soils)
C_i = 12 x EC_i
= 12x(1.6+1.57+1.6+1.9)/4 = 20.01 me/l
C_{FC} = 2x12(20+9.3+11)/3
= 322.4 me/l
Substituting the above values in equation

LR = 1150x20.010/0.4(322.4-20.01) = 190.2 mm
Dividing this by 31 (No. of days in December),
The drainage coefficient DC is obtained as

DC = 190.2/31= 6.14 mm/day= 0.00614 m/day

Due to flat topography, bunded rice fields and absence of surface drainage, the whole of monthly P was considered effective.

Percolation rate from the rice field is 0.012 m/day the possible drainage coefficients work out on various approaches are summarized in Table1

Table 1. Estimated drainage coefficients DC (m/day) by different approaches
Basis of estimation of DC

Particulars	DC, m/day
In- situ saturated hydraulic conductivity	0.144
Basic infiltration rate on initially dry soil	0.02888
Leaching requirement	0.00614
Percolation in puddle paddy fields	0.012

From the above table1, minimum i.e. 0.00614 m/day will be governing recharge rate and is adopted as an initial guideline as drainage coefficient for sub-surface drainage system.

The investigations revealed that sand was encountered beyond a depth of 1 m. the sand layer was of unknown thickness (tested down to 3 m). Hence, the depth of drain was taken as 1 m and depth of impermeable layer as 3.5 m. Since paddy roots are considered effective down to 30 cm from the surface and drain depth has been taken as 1 m, the hydraulic head is taken as 0.5 m, leaving a 20 cm depth of profile below the root-zone to account for capillary rise. For steady state conditions depicting drains flows equality rainfall recharge, Hooghoudt's equations have been used. The steady state drainage equations (Mostly the equations proposed by Hooghoudt's) are based on the important assumption that the drain flows are governed by Darcy's law for a stabilized inflow (rainfall recharge) and over equal outflow (drainage coefficient). Also, the soil is considered to be a homogeneous medium with isotropic hydraulic conductivity. The steady state equations generally do not incorporate the effect of drainage porosity, which is a very important design parameter for true drainage conditions that conform to unsteady state flow. While the study state approach only depicts a simplified, constant relationship between the water table and the drain discharge, the practical situations impose temporal variations in recharge to water table resulting in unsteady flow of ground water towards the drain (both the unsteady state approach are based on the same Dupuit. Forchheimer assumption. The only difference is that the recharge varies with time in unsteady state flows.

De Zeeuw- Hellinga equation is used to describe a fluctuating water table, typical situation humid areas with high intensity rainfall concentrated in discrete storms. In this approach, a non-uniform recharge is divided into shorter time period in which the recharge to the groundwater can be assumed to be constant. Both these situations prevail in the study area. Hence, the unsteady state drainage analysis has been carried out by above-mentioned equations.

Layout of Subsurface Drainage System

The practical layout of a subsurface drainage system should encompass proper alignment and possessing of drain laterals, collector pipes and other intermediate control structures. Care should be taken to ensure that the drainage system installed does not hamper the regular farming operations the layout should also indicate the position of collector points and outlets. The layout should also accommodate for easy modes of observations related to soil properties, water table fluctuations, hydraulic gradient and drain outflows.

As seen from the following Figures 3 - 8, prior to the monsoon of 1997, the system was laid out in 4.0 ha area adjacent to previously taken area of 3.2 ha was put under sub-surface drainage experiment. Baked clay tiles with 6 mm dia perforators 80 mm part on one-third of the periphery in three rows, and 10 cm inner diameter with the bell mouth at one end were used as laterals. The spacing were at 35 m and 55 m apart. The length was 120 m. slope was 0.2 per cent the filters used were river sand along the trench and 100 gms coir fibre at the pipe joints

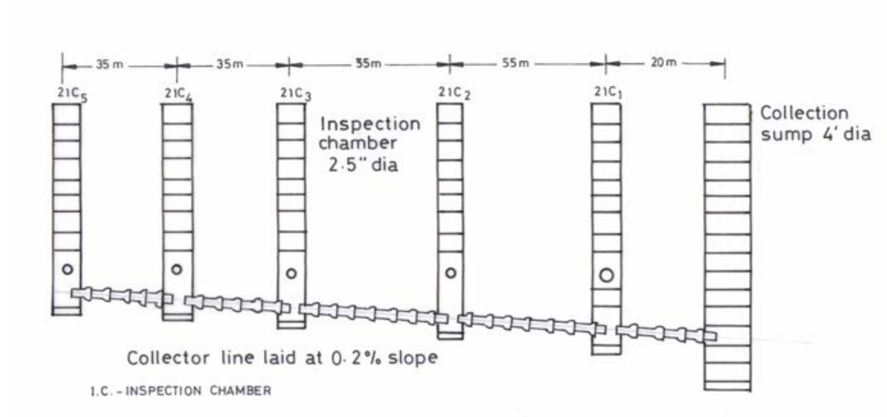


Figure 3. Cut section along collector line

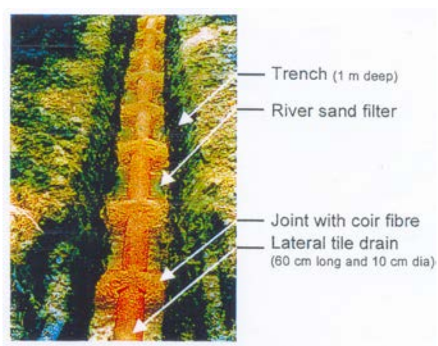


Figure 4. Laying of subsurface drains

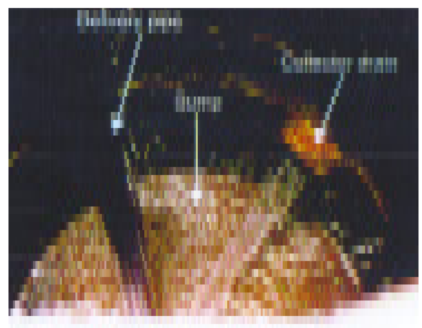


Figure 5. Free flow of collector drain into sump

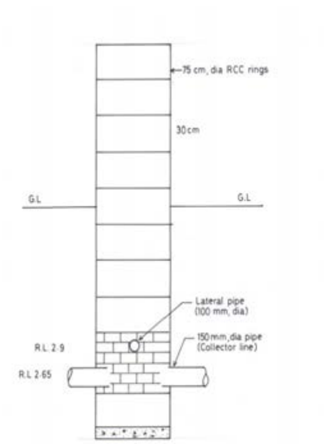


Figure 6. Cut section of inspection chamber

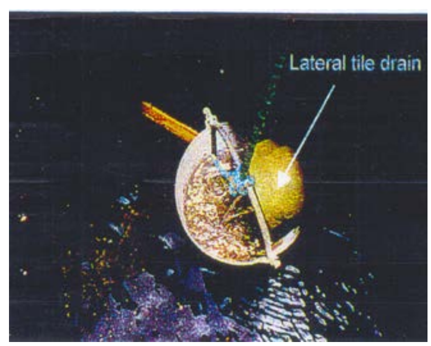


Figure 7. Discharge Measurement in inspection chamber

Each pipe was 60 cm length the laterals were joined to a collector line through sump, inspection chambers made of standard size (0.75 cm dia and 0.3 m height) concrete rings. The collector pipe was of baked clay had an internal diameter of 15 cm with bell mouth at one end and without perforations, was laid at a slope of 0.4 per cent and discharged into a sump well of concrete rings from which the leachate was pumped out into an existing shallow pen drain. Adequate care was taken to maintain the uniformity of the slopes in the lateral and collector line and to negotiate each joint. The bottom of the sump well and the inspection chambers were sealed with cement concrete and were kept sufficiently below the lateral and collector outlet to enable monitoring of the discharge from the drains. The drained water collected in the main sump was pumped out to main drain canal. The main drain water draws towards aquaculture site.

To monitor water table, observation wells installed at half and one- fourth spacing from the lateral and one very close to the lateral.

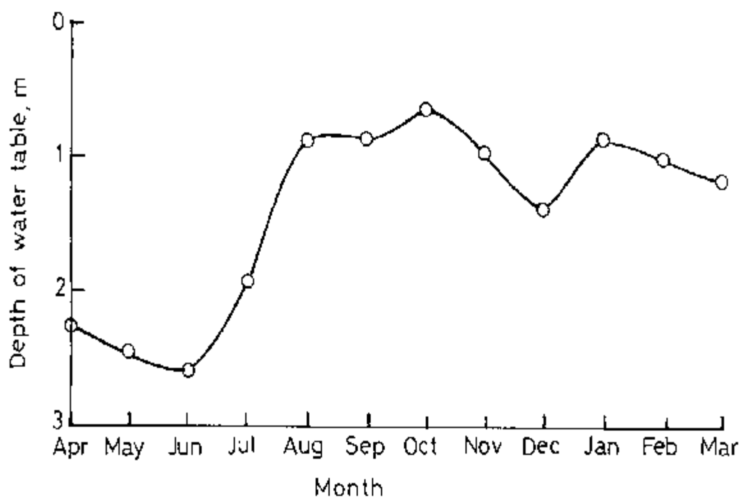


Figure 8. Ground water fluctuations in the project

For simulation, De Zeeuw- Hellinga equation was used keeping in view of the recharge a effective rainfall (m) average water table depth and the drain discharge (m/day) for the 3 consecutive years from 1998-2000. Rainfall data for study are was obtained from meteorological laboratory and the average values for 3 years i.e. 1998-2000 were worked in month wise and the program was prepared C++ version and ultimately the average water table values and drain discharge values were worked out. The reference drainable porosity in kept at 10 per cent.

REFERENCES

AICRIPAD.1986-1988. *Annual reports.* All India Coordinated Research Project on Agricultural Drainage Under Actual Farming Conditions on watershed basis, Agricultural Research Station, A.P. Agril.University, Machilipatnam, Andhra Pradesh, India

Belmans, C., Wesseling, J.G. and Feddes, R.A., 1983. Simulation model of the water balance of a cropped soil. SWATRE, *Journal of Hydrology,63:* 271-286.

Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. S*oil Science*, *117*:311-314.

Devadattam, D.S.K. and Ramesh Chandra, S.1995. *Agricultural Land Drainage in Coastal Saline Soils, AICRP on Agril.* Drainage Agricultural Research Station, Machilipatnam, A.P.Agril.University, Rajendranagar, Hyderabad.

Evans, R.O. and Skaggs, R.W. 1993.Stress day index models to predict corn and soybeen yield to water management.In:15th International Congress of International Commission on Irrigation of Drainage (ICID).The Hague, Workshop on Sub surface Drainage Simulation, Models, ICID-CIID.

Feddes, R.A. 1987. Simulating water management and crop production with the SWACRO model. P*roceedings Third International Workshop on Land Drainage.* The Ohio State Universiy, Columbus, Ohio, USA December 7-11,1987,A 27-40.

Great Plains Systems Research .1992. Root Zone Water Quality (RZWQ) model. Technical Documentation. GPSR. Tech. Report. USDA-ARS. Fort Collins, Colorado, USA.

Haan, C.T., Johnson, H.P. and Brakensick,D.L.1982. *Hydrologic Modeling of Small Watersheds.* An ASAE monograph Number 5, ASAE, 2950 Niles Road, P.O. Box 410, St. Joseph, Michigan 49085, USA.

Jarvis, N.J. and Leeds-Harrison, P.B.1987, Modelling water movement in drained clay soil. Description of the model sample output an sensitivity analysis. *Journal of Soil Science*, 38:487-498.

Kamra, S.K., Singh, S.R., Rao, K.V.G.K and van Genuchten, M.Th. 1991a. A semidiscrete model for water and solute movement in tile drained soils.1.Governing equations and solutions. *Water Resources Research,*27(9):2439-2447.

Leeds-Harrison, P.B., Shipway,C.J.P., Jarvis, N.J. and Youngs, E.G.1986.The influence of soil macro porosity on water retention, transmission and drainage in a clay soil. *Soil Use and Management,*2:47-50

Oosterbaan, R.J.1989. SALTMOD. *AnnualReport,* ILRI, Wageningen, The Netherlands, December, pp.1-49.

Parsons, J.E. and Skaggs, R.W. and Gilliam , J.W.1989. Pesticide fate with DRAINMOD CREAMS. *Proceedings of the CREAMS /GLEAMS Symposium.* Publication no.4,123-135.Tifton,GA:UGA-CPES.

Ramaswamy, K.1993.Studies on salt dynamics of agricultural fields under subsurface drainage. Unpublished Ph.D.Thesis. Division of Agricultural Engineering, Indian Agricultural Research Institute, New Delhi,134p.

Rao, K.V.G.K., Ramesh,G., Chauhan,H.S. and Oosterbaan, R.J.1992. Salt and water balance studied to evaluate remedial measures for waterlogged saline irrigated soils. Proc. of the 5th International Drainage Workshop, Lahore, Pakistan, ICID & CHD II, pp.267-277.

Tanton, T.W., Rycroft, D.W. and Hashimi, M.1995. Leaching of salt from a heavy clay subsoil under simulated rainfall conditions. *Agricultural Water Management,* 27:321-329.

Williams,E.J., Hutchinson, G.L. and Fchsenfeld, F.C.1992. NO and Nitrous oxide emissions from soil. *Global Biogeochem Cycles,* 8:351-388.

Youngs, R.A., Onstad,C.A., Bosch, D.D. and Anderson,W.P.1989. AGNPS: A nonpoint source pollution model for evaluating agricultural watershed, *Journal of Soil Water Conservation,* 44920:168-173.

Zimmer, D., Lorree, E. and Leasaffree, B. 1995. Parameter sensitivity and field evaluation of SIDRA model. *Irrigation and Drainage Systems* ,9:279-296.

MANAGEMENT STRATIGIES FOR THE REUSE OF WASTEWATER IN JORDAN

Mohammad M. Duqqah[1]
Khaled M. Bali[2]
Ayman A. Suleiman[3]

ABSTRACT

Water resources in Jordan are extremely limited and water availability per capita is among the lowest in the world. With the expected growth in population, the already limited supply of fresh water for agriculture will be used to meet the growing demands in urban and industrial regions of the country. The sustainability of irrigated agriculture in Jordan is dependent on efficient irrigation systems such as drip irrigation and marginal water sources such as wastewater generated from wastewater treatment facilities in Jordan. The municipal and industrial water requirements in Jordan are expected to increase by 65% over the next 15 years. While agricultural demands are expected to increase by 5% during the same period. Reuse of treated municipal water is expected to increase to meet the growing urban, industrial, and agricultural demands in the future.

Irrigated agriculture in Jordan is mostly concentrated in the Jordan Valley with optimum climatic conditions that allow for the production of up to three high-value vegetable crops per year. As irrigated agriculture in Jordan becomes more dependent on wastewater and other marginal water sources, the quality of marginal waters used for irrigation must be suitable for crop production. Therefore, the availability of treated wastewater for reuse to meet crop water requirements is dependent on water quality, crop type, irrigation system, and other factors. A computer model was developed to predict the potential contribution of wastewater to crop water use of major cash crops in the Jordan Valley. The model incorporates wastewater quality, irrigation system, crop type, and soil type in estimating the maximum potential contribution of wastewater to crop evapotranspiration. The model estimates the potential quantities of wastewater that can be used to supplement fresh irrigation water for each of the major crops in the Valley. The model can be used to implement sustainable management strategies for the reuse of treated wastewater in the Jordan Valley.

INTRODUCTION

Irrigated agriculture in Jordan has been growing rapidly. The available fresh water supplies in Jordan were approximately 826 million cubic meter (MCM) in 2003 of which 520 MCM were used in agriculture (63.5 % of the total water use in Jordan). Urban water uses accounted for approximately 32.5% while industrial uses accounted for 4%. In the year 2010, the annual

[1] Faculty of Agriculture. University of Jordan. Amman-Jordan. Tel: 962-6-535-000 Ext. 2583. Email: mmduqqah@ju.edu.jo.
[2] University of California Desert Research & Extension Center, 1050 E. Holton Rd. Holtville, CA 92250. Tel: 760-352-9474, Fax: 760-352-0846. E-mail: kmbali@ucdavis.edu.
[3] Faculty of Agriculture. University of Jordan. Amman-Jordan. Tel: 962-6-535-000 Ext. 2554. Email: ayman.suleiman@ju.edu.jo.

potential available water resources are estimated to be 1219 MCM, while the estimated total water requirements are expected to increase to 1538 MCM. Irrigated agricultural sector will consume about 68 % of the total available water resources (MWI, 2003). The total available water resources per capita are decreasing as a result of population growth (annual rate of 2.5% in 2004) and are projected to fall from the current 160 m^3/capita/year to about 90 m^3/capita/year by the year 2025.

STUDY AREA

Jordan's total area is about 88,778 km^2, located about 80 kilometers east of the Mediterranean Sea (DOS, 2006). More than 80 % of the country's area is arid and receives less than 200 mm annual rainfall. The average precipitation over Jordan is about 93.6 mm. Generally, the climate is Mediterranean, with a long dry hot summer, a rainy winter, and a relatively dry spring and autumn seasons. Irrigated agriculture in Jordan (76,000 ha) falls under two categories in term of management and source of water. In the highlands (43,000 ha), privately managed individual farms are irrigated by groundwater from private wells. In the Jordan Valley (33,000 ha), the publicly managed irrigation system uses surface water of Yarmouk River and side wadis as well as recycled wastewater. Agricultural development in Jordan depends mainly on the availability and quality of water resources, and this requires further development of irrigation water management (Jitan, 2005).

REUSE OF WASTE WATER IN JORDAN

As irrigated agriculture in Jordan becomes more dependent on wastewater and other marginal water sources, the quality of marginal water used for irrigation must be suitable for crop production. In addition, the quality of marginal water that is discharged into waterways is expected to meet minimum standards to achieve water quality objectives and uses for a particular watershed. The water quality constituents of major concerns for irrigated agriculture in Jordan include suspended sediment, salinity, nutrients (mainly P and N), Na, Cl, SO_4, HCO_3, B, trace elements, heavy metals, pathogens, and high pH.

Some marginal water sources that are not suitable for irrigated agriculture, because of the high load of salts or other constituents such as sodium or chloride, are either discharged into waterways or mixed with fresh irrigation water and used for irrigation. While such waters are not suitable for irrigating vegetable crops, using relatively simple treatment methods could significantly reduce the load of sediment, phosphorus and nitrogen. Wastewater sources that are high in salinity are not suitable for vegetable crops could be used to irrigate forages and field crops.

The reuse of wastewater may provide practical and cost-effective solutions to the increasing demand for additional water in Jordan. The Government of Jordan and the USAID mission in Jordan have identified the reuse of wastewater for irrigation as a high priority issue (USAID Website). Reuse of wastewater and other marginal waters will increase the availability of freshwater for urban and industrial users in Jordan. Irrigated agriculture in Jordan is mostly concentrated in the Jordan Valley with optimum climatic conditions that allow for the production of two to three high-value vegetable crops per year.

WATER QUALITY AND WATER USE ASSESMENT

With the expected increase in population, the amount of reclaimed water or treated wastewater discharged into Wadi Zarqa (King Talal Reservoir) are projected to triple by the year 2025 (McCornick, et al., 2002). Most of this treated wastewater that is discharged into King Talal Reservoir (KTR) and mixed with natural runoff waters, relatively saline springs, and reclaimed water from other urban areas including Amman, the capital of Jordan (McCornick, et al., 2002). The salt and nutrient contents of this water are relatively high and have greater impact on crop production as compared to fresh irrigation water. The quality of KTR water is expected to change in the future because of the expected increase in the quantity of treated wastewater discharged into the reservoir. KTR water is mostly used in the southern part of the Jordan Valley. Water quality parameters of KTR are listed in Table 1. The northern part of the Jordan Valley receives higher quality waters from the Yarmouk River, Mukheibeh wells, and Wadi A Arab Reservoir, and are collectively referred to as King Abdullah Canal (KAC) waters (McCornick et al. 2003). KAC waters are also used in urban areas because of the relatively lower salinity content of the water (Table 1)

Table 1. Water quality parameters of King Talal Reservoir (Grattan, 2000 and McCornick, 2003)

Water Quality Parameter	*Unit*	*KTR (1994-99)*	*KAC (1997-99)*
EC	dS/m	1.9	0.98
PH	-	7.8	8.2
SAR	-	3.8	2.1
TSS	mg/l	20	56
Na	mg/l	190	86
Ca	mg/l	117	71
Mg	mg/l	46	30
K	mg/l	29	8.5
Cl	mg/l	322	124
SO4	mg/l	139	86
HCO3	mg/l	508	282
Total P	mg/l	5.6	0.4
PO4-P	mg/l	4.9	0.3
Total N	mg/l	26.0	4.3
NO3-N	mg/l	2.0	3.1
NH4-N	mg/l	19.0	1.0

Irrigation water quality in the northern part of the Jordan Valley is relatively good and has little to no impact on crop productivity. However, as the demand for water increases in the urban and industrial sectors, the amount of fresh water available for irrigated agriculture will decline. Reuse of wastewater in the northern part of the Jordan Valley will continue to increase. In the southern part of the valley, the quality of water available for irrigation is relatively high in salinity and other constituents that require careful selection of appropriate crops, irrigation systems, and management practices to maintain productivity.

Assessment Method

The hazard index concept has been used to establish a vulnerability assessment process for nitrate in groundwater at the watershed scale (Nolan 2001). The concept of establishing a nitrate groundwater pollution hazard index is also appropriate at the farm scale (UC Center for Water Resources, 2004). Estimates of vulnerability can be separated into intrinsic vulnerability and specific vulnerability (National Research Council, 1993). Intrinsic vulnerability is related to factors of which the grower has no control such as soil properties, hydrologic factors, and irrigation water quality. For a given crop, the crop has an intrinsic vulnerability for salinity or specific ion toxicity. Specific vulnerability is a function of management factors such quantity, rate, and method of water and fertilizer applications and other management factors that can be controlled by the farmer.

A wastewater reuse hazard index (WRHI) was developed by Bali and Duqqah (2007) to provide farmers in the Jordan Valley with management tools that can be used to reduce the potential negative impact of wastewater on crop productivity. The overlay and index method of UC Center for Water Resources (2004) was used to assign hazard value for each variable that affect crop productivity. Each variable was assigned a hazard value ranging from 0 to 5. The WRHI is a sum of the hazard values of all factors. The following parameters were used to establish hazard indices for various wastewaters in Jordan:

1- Salinity of irrigation water: The relationship between salinity (EC, electrical conductivity is an estimate of salinity) of irrigation water and crop yield is well established (Bali, 2003). In general field crops are more tolerant to salinity than vegetable crops. The hazard index for salinity will is dependent on crop type and salinity of irrigation water. The yield-salinity response functions of Maas and Hoffman (1977) and van Genuchten and Hoffman (1984) were used to generate hazard values based on salinity and crop type. For example a wastewater with salinity of 2 dS/m has no impact on alfalfa yield (alfalfa is moderately sensitive), therefore a salinity hazard value of zero (0) is appropriate. However, the same water is expected to reduce the yield of green bean (sensitive) by 19%, therefore a salinity hazard value of 1 or higher is appropriate for bean.

2- Specific ion toxicity: Some crops are sensitive to specific ions such as Na, Cl, and B. Specific ion toxicity depends on the concentration of the ion in irrigation water, crop type, and in some cases, the type of irrigation system. For example, the toxicity effect is compounded if the crop is irrigated by a sprinkler system but not a problem with drip irrigation. Chloride concentrations in excess of 250 mg/l pose threats to rootstocks on citrus and grapes (Ayers and Westcot, 1985). The hazard index for each of the above ions were dependent on the factors specific to each ion and each crop.

3- Trace elements: Trace elements are generally present at very low concentrations in surface water sources. However, the concentrations are relatively high in wastewater. A hazard index value was established for each major trace element found in wastewater. According to Grattan (2000), the current levels of trace elements found in wastewater in Jordan have little impact on the productivity of agriculture in Jordan at the present time. A hazard value index for each of the major trace elements was established. The index was based on the recommended maximum concentrations of 15 trace elements in irrigation water for the long-term protection of plants and animals (Pratt and Suarez, 1990).

4- SAR: The impact of Sodium Adsorption Ratio on soil structure depends on the value of SAR, EC, and soil type. The impact of SAR-EC on soil infiltration is well documented in the literature. We used the salinity concentration-SAR relationships established by Rhoades (1982) to assign hazard values to various soil types found in the Jordan Valley. A hazard value index was established for SAR, the index was function of EC and soil type.

5- Nutrients: Wastewater is rich in nutrients specially nitrogen and phosphorus. The nutrient hazard index was based on the concentration of plant available levels of N. Another hazard index was established based on the concentration of soluble P in wastewater. Another area of concern is the presence of P in suspended sediment and the potential for algal blooms in waterbodies and potential impact on the irrigation systems (example, clogging of drip emitters).

6- Irrigation system: A hazard index for the irrigation system depends on the type of irrigation system. For example, the hazard value for a surface or flood system is low, while the hazard value for a drip system is relatively high. The potential interactions of other factors such as pH, HCO3, and total suspended solids was considered.

7- Total Suspended solids (TSS). The presence of suspended sediment and other contaminates adsorbed on suspended sediment in waterways has multiple negative impacts on water quality and may cause environmental problems (Davies-Colley and Smith, 2001). The 1998 National Water Quality Inventory ranks suspended solids and sediments as the leading cause for water quality impairment of rivers and lakes in the United States (Swietlik, 2002). The presence of TSS in water depends on many factors. Bali et al. (2005) studied the interaction between TSS and runoff events in agricultural watershed in Southern California. The relationship between TSS and natural runoff events are not well established and depends on the particle size distribution of sediment and flow rate. In Jordan, TSS values are relatively high in late winter and 75% of all farms in Jordan experience significant plugging problems after two years of use (Hagan and Taha, 1997). In addition to the negative impact of TSS on drip filters and emitters, P is tied up in the suspended sediment and increases the potential for algal bloom. A hazard index for sediment will be established, the index will be a function of the particle size distribution of TSS in wastewater (Bali et al., 2005).

Model Assessment

A WRHI model was developed to integrate the above factors to provide growers in Jordan with a single WRHI for a given crop and estimate the maximum amount of wastewater that could be safely used to meet crop water requirements. For example, WRHI between 0 and 10 for a given crop is of relatively minor concern and no extraordinary management measures are required. However when the WRHI for the same crop increases beyond 10 due to high levels of TSS in the water, the grower will get a detailed report on the hazard of TSS and what measures could be used to bring the WRHI to value below 10. For example, when the concentration of TSS is high, the WRHI is 13. The grower can implement a management measure to flush the media filter twice as often when the value of TSS is low. This management measure reduces the WRHI to an acceptable and economical level to sustain agricultural productivity. Another measure that could be used is sedimentation basin.

Figure 1. shows a sample output of the model for five different management strategies that can be implemented to reduce the WRHI for wastewater and the costs associated with each measure. While all of the management measures are effective in reducing the hazard index for specific wastewater, management measure 2 (BMP 2) is the most cost-effective measure.

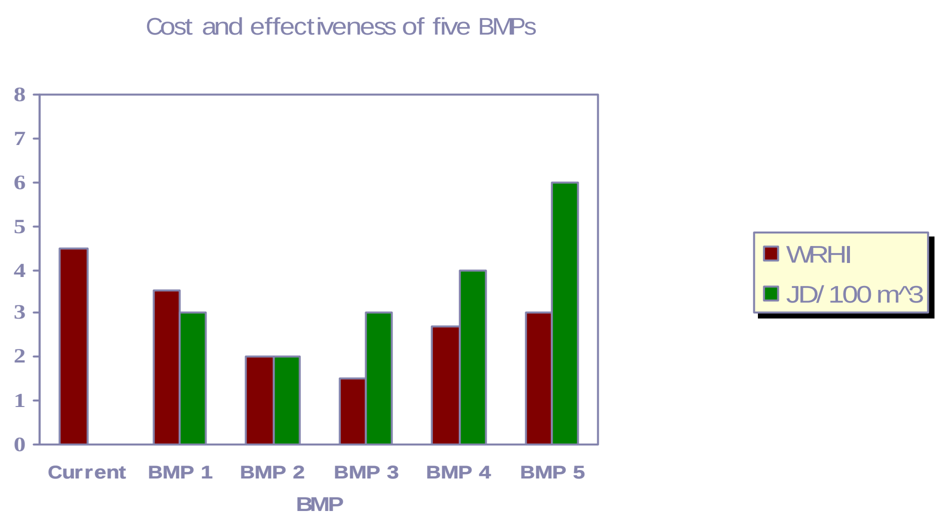


Figure 1. Sample assessment of five management practices to reduced the hazard index of wastewater for a sample farm.

CONCLUSIONS

Irrigated agriculture in Jordan is dependent on wastewater and as a result the quality of marginal water used for irrigation must be suitable for crop production. The availability of treated wastewater for reuse to meet crop water requirements is dependent on water quality, crop type, irrigation system, and other factors. A computer model was developed to predict the potential contribution of wastewater to crop water use of major cash crops in the Jordan Valley. The model incorporates wastewater quality, irrigation system, crop type, and soil type in estimating the maximum potential contribution of wastewater to crop evapotranspiration. The model estimates the potential quantities of wastewater that can be used to supplement fresh irrigation water for various major crops in the Jordan Valley. The model can be used to implement sustainable management strategies for the reuse of treated wastewater in the Jordan Valley.

REFERENCES

Ayers, R. S. and D. W. Westcot. 1985. Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. FAO, United Nations, Rome. 174 pp.

Bali, K. M. 2003. Saline Water. *Encyclopedia of Water Science.* New York. Marcel Dekker, Inc. pp 829-831.

Bali, K. M. and M. M. Duqqah. 2007. Wastewater Reuse Hazard Index for Wastewater in Jordan. Proceedings of the 6th International Conference. University of Jordan. April 2007.

Bali, K. M., P.Gao, G. B. Pasternack, and W. W. Wallender. 2005. Calibration and Use of In Situ Turbidity Sensors For Estimating Sediment Load In Drainage Waters. In the Proceedings of the SCADA and Related Technologies for Irrigation District Modernization Conference. USCID. October 26-29, 2005. Vancouver, Washington. 9 pages.

Davies-Colley, R. J., and D. G. Smith, 2001. Turbidity, Suspended Sediment, and Water Clarity: a Review. Journal of the American Water Resources Association 37: 1085-1101.

DOS (Department of Statistics, Jordan). 2006. Annual report, Department of Statistics, Amman, Jordan.

Grattan, S. R. 2000. Impact of Increasing Supplies of Reclaimed Water on Crops, Soils and Irrigation Management in the Jordan Valley. Water Policy Support, Ministry of Water and Irrigation, Amman Jordan. 60 pp.

Hagan, R. E. and S. S. Taha. 1997. Irrigated Agriculture in Jordan; Background Paper. Water Quality Improvement and Conservation Project. Report 3114-97-3b-19.

Jitan, M. A. 2005. Evapotranspiration of major crops in the Jordan Valley using remote sensing techniques compared with estimated field measurement using Eddy- Correlation. Ph.D. Thesis, University of Jordan, Amman, Jordan.

Maas, E. V. and G. J. Hoffman. 1977. Crop Salt Tolerance-Current Assessment. *Journal of Irrigation and Drainage Engineering, ASCE* 103(IR2):115-134.

McCornick, P. G., S. S. Taha, and H. El Nasser. 2002. Planning for Reclaimed Water in the Amman-Zarqa Basin and Jordan Valley. ASCE-EWRI Conference and Symposium on Drought and Fllods, Roanoke, Virginia.

McCornick, P. G., S. R. Grattan, and I. Abu-Eisheh. 2003.Water Quality Challenges to Irrigated Agriculture Productivity in the Jordan Valley. Proceedings of the 2nd International Conference on Irrigation and Drainage-Water for a Sustainable World-Limited Supplies and Expanding Demand. USCID. May 12-15, 2003. Phoenix, Arizona. pp 333-343.

MWI (Ministry of Water and Irrigation, Jordan). 2003. Annual Report, Amman, Jordan.

National Research Council. 1993 Groundwater Vulnerability Assessment-Predicting Relative Contamination Potential Under Conditions of Uncertainty. National Academy Press. Washington, DC.

Nolan, B. T. 2001. Relating Nitrogen Sources and Aquifer Susceptibility to Nitrate in Shallow Ground Waters of the United States. Ground Water. 39(2):290-299.

Patt, P. F. and D. L. Suarez. 1990. Irrigation Water Quality Assessments. In Agricultural Salinity Assessment and Management. K.K. Tanji (editor). ASCE Manuals and Reports on Engineering Practice No. 71, ASCE, New York. Pp 220-236.

Rhoades, J. D. 1982. Reclamation and management of salt-affected soils after drainage. Proceedings of the First Annual Western Provincial Conference. Rationalization of Water and Soil Resources and Management. Lethbridge, Alberta, Canada. Nov. 27-Dec.2; pp.123-197.

Swietlik, W., 2002. Managing turbidity, suspended solids and bedded sediments under the clean water act– the EPA perspective. Turbidity and Other Sediment Surrogates Workshop, April 30 – May 2, 2002, Reno, NV.

USAID mission in Jordan. 2005. http://www.usaidjordan.org

UC Center for Water Resources, 2004. Nitrate Groundwater Pollution Hazard Index- The Hazard Index Concept. 4 pp.

Ven Genuchten, M. Th. and G. J. Hoffman. 1984. Analysis of Crop Salt Tolerance Data. Soil Salinity Under Irrigation-Process and Management (I. Shainberg and J. Shalhevet, editors). Ecological Studies 51, Springer-Verlag, New York. pp 258-271.

RECLAMATION OF SALINE AND WATERLOGGED SOILS IN MUTLURU CHANNEL COMMAND OF KRISHNA WESTERN DELTA, ANDHRA PRADESH STATE, INDIA

P.R.K. Prasad[1]
D. Srinivas[2]
T.V. Satyanarayana[3]
S. Ramesh Chandra[4]
G. Subba Rao[5]
B. Mukunda Rao[6]
A. Srinivasulu[7]

ABSTRACT

There is about 35,000 ha of salt-affected, water logged lands in the irrigated command of Krishna Western Delta in Andhra Pradesh state of India. A pilot study of installing open subsurface drainage to improve crop yields was conducted in 22.3 ha. of the Mutluru Channel Command. In this Pathareddy Palem drainage pilot area, the 0.25-0.35 m. deep open drain laterals were spaced from 60 to 80 m apart. Paddy rice was grown during the kharif season (July-November monsoon cropping season) of 2005 and 2006. The paddy rice grain yield was 2.2 t ha^{-1} during pre-drainage, and after drainage, increased to 2.9 and 3.8 t ha^{-1} in the kharif 2005 and 2006 seasons, respectively.

Eight observation wells, installed to 3.4 m depth in Mutluru channel command and measured weekly, showed that the water table at near ground surface was lowered to as much as 3 m depth and EC of the ground water ranged from 18 to 44 dS/m. Soil ECe was measured at grid sites sampled at 0-15, 15-30, 30-60 and 60-100 cm depth intervals. In the summer of 2005 about 6% of the 62 samples were non saline (< 4 dS/m) and 19% had ECe ranging from 4-8 dS/m. In the summer of 2006, 29% of the samples were non saline and 15% had ECe of 4-8 dS/m. The open subsurface drainage system helped in leaching soluble salts from the root zone increasing the paddy grain yields. This pilot project proved that installation of open surface drainage systems in the Krishna Western Delta Command will be beneficial to crop production and increase economic returns to farmers.

---

[1]Principal Scientist (Soil Science), A.P..Water Management Project (The Netherlands Assisted FAO Project), Bapatla, Andhra Pradesh, India (prk_prasad@yahoo.com)
[2] Senior Scientist (Soil Science), RARS, Maruteru, West Godavari District, Andhra Pradesh, India
[3]Principal Scientist (SWE) and Project Manager, A.P. Water Management Project (The Netherlands Assisted FAO Project), Bapatla, Andhra Pradesh, India
[4] Scientist (SWE), A.P. Water Management Project (The Netherlands Assisted FAO Project), Bapatla, Andhra Pradesh, India
[5] Senior Scientist (Agronomy), A.P. Water Management Project (The Netherlands Assisted FAO Project), Bapatla, Andhra Pradesh, India
[6] Formerly Scientist (Agric. Extension), A.P..Water Management Project (The Netherlands Assisted FAO Project), Bapatla, Andhra Pradesh, India
[7]Formerly Scientist (SWE), A.P. Water Management Project (The Netherlands Assisted FAO Project), Bapatla, Andhra Pradesh, India.

INTRODUCTION

The state of Andhra Pradesh, situated on the southern coast of India, extends from $12^0$37' to $19^0$54' North latitude and $76^0$46' to $84^0$46' East longitude with a total geographical area of 2,74,000 km^2 with a population of 100 million. It comprises of three geographical regions, namely, the coastal Andhra, Rayalaseema and Telangana. Andhra Pradesh is the fifth largest state, accounting for 8.4 percent of the country's area. Seventy seven per cent of the population is dependent on agriculture, contributing 60 per cent of the state income. About 42 per cent of the geographical area is under cultivated crops. The state has the longest coastal line of 972 km along its eastern border with three perennial rivers, i.e., Krishna, Godavari, Penna and five minor rivers draining into the Bay of Bengal. Based on the elevation contours, the state has been divided into three physical regions called coastal plains, peninsular plateau and eastern ghats (terraces).

The total salt-affected area in the state is estimated to be about 8.18 lakh (10^5) ha. The irrigation-induced water logging and salinity were estimated to be 2.72 and 1.15 lakh ha, respectively, and these are the two major causes leading to crop yield declines in most of the irrigation commands. Further, continuous irrigation over the years without adequate drainage has caused the rise of ground water table into root zones, reducing crop yields.

The irrigation-induced water logging and salinity are relatively recent features in most of the commands. Adoption of proper water management practices coupled with provision of appropriate drainage could mitigate this problem. To test and demonstrate the drainage need for control of soil salinity and water logging, a collaborative project with Alterra, ILRI, The Netherlands, was approved by the Government of Andhra Pradesh with ANGRAU and Bapatla as a main center.

This center is entrusted with the responsibility of solving the water logging and salinity problems by installation of subsurface drainage (SSD) systems in the canal commands of Andhra Pradesh.

Krishna Western Delta

The Krishna delta irrigation system is one of the earliest major irrigation projects in Southern India. It consists of an anicut (dam) on the river Krishna at the present Barrage site near Vijayawada, Krishna District (Revenue Division) that was designed by Sir Arthur Cotton during the years 1852-55. The scheme irrigates an ayacut (command area) of 5.14 lakh ha in the West Godavari, Krishna, Guntur and Prakasam districts, converting the Krishna delta into the richest granary in Andhra Pradesh. The Krishna delta irrigation system comprises of two components viz. Krishna Eastern Main Canal System (2.72 lakh ha ayacut) and Krishna Western Main Canal System (2.42 lakh ha ayacut). The Krishna Western Delta (Krishna western main canal command) covers Guntur district and a small part of Prakasam district in the state of Andhra Pradesh. Irrigation water in the command area is released from the Prakasam barrage at Vijayawada. The location map of Krishna Western Delta is shown in Figure1.

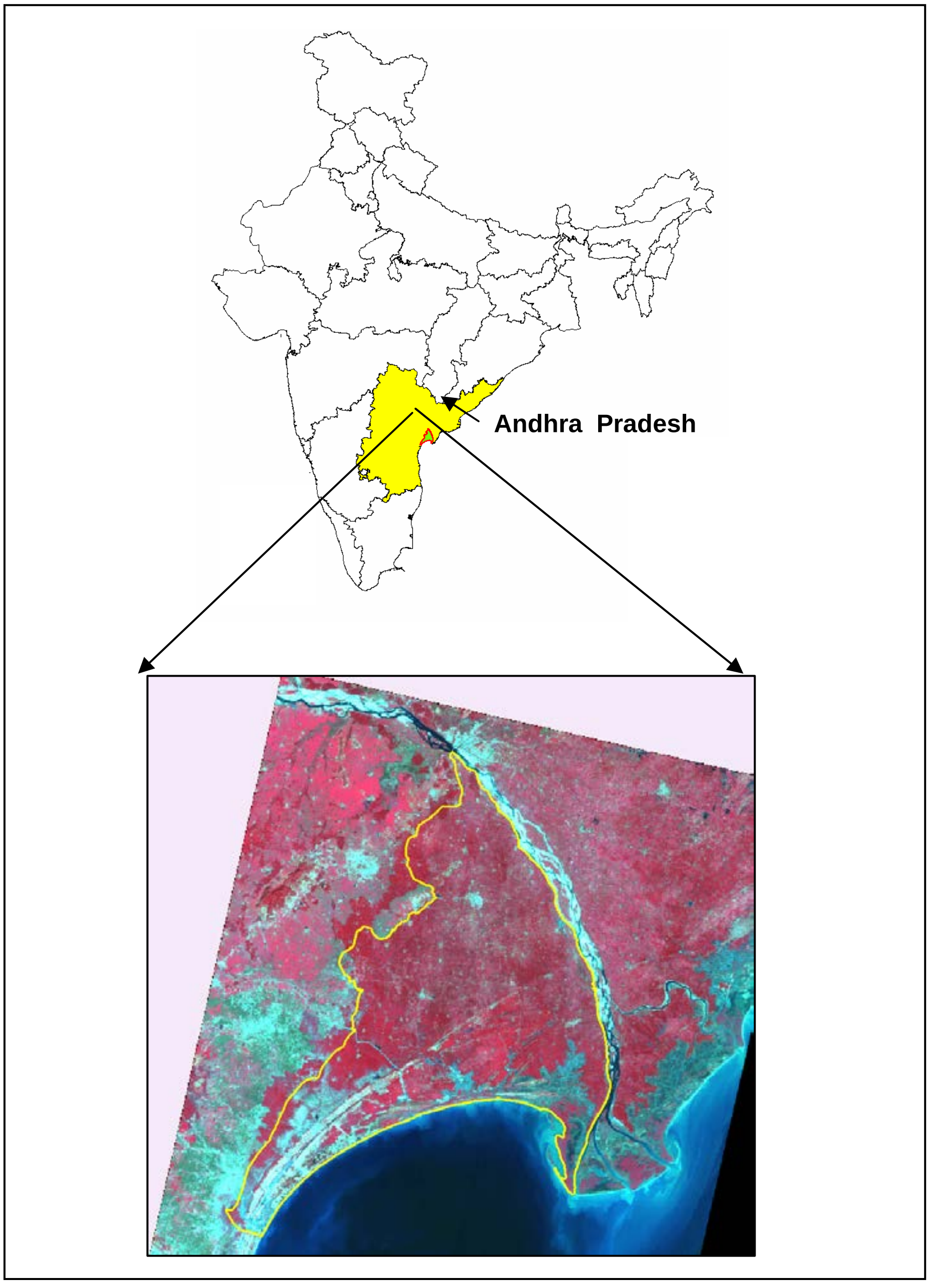


Figure.1 Location Map of Krishna Western Delta, Andhra Pradesh, India.

MATERIALS AND METHODS

The total command of Mutluru channel command is 1135 ha out of which 22.3 ha was selected as a pilot area for installation of an open subsurface drainage system

Grid Sampling

A grid survey was conducted at an interval of 60 x 60 m in the proposed drainage pilot area of 22.3 ha (Fig.2). Sixty two soil samples were collected from the grid locations at 0-15 cm, 15-30 cm, 30-60 and 60-100 cm depths. The soil samples were analyzed for pH, ECe, water-soluble cations and anions, ESP, and available macro and micronutrients following standard procedures described by Black (1965) and Richards (1954).

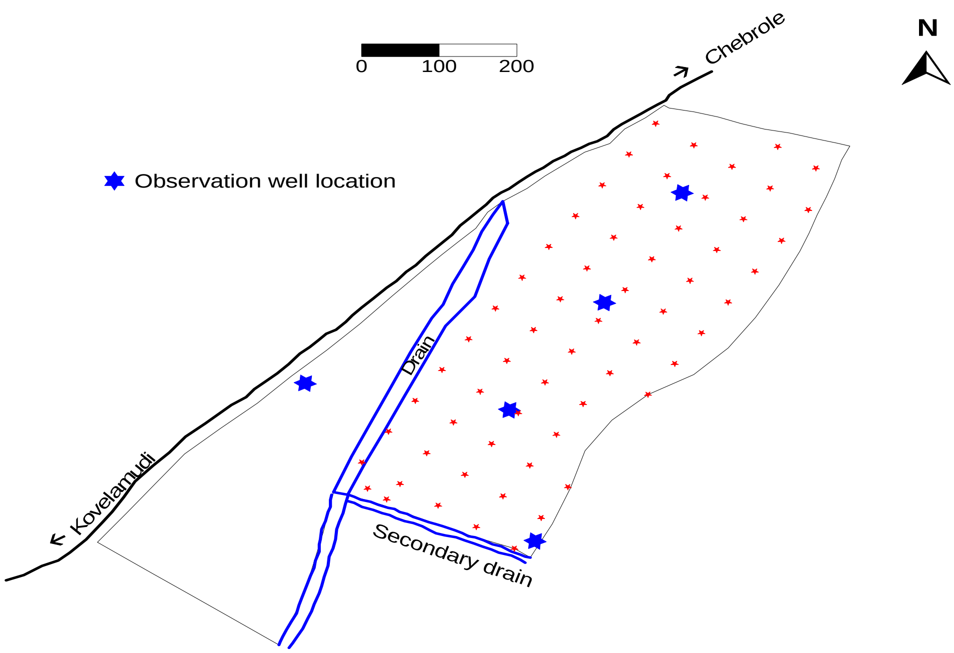


Figure 2. Map showing the grid soil sample locations of Pathareddy Palem drainage pilot area

Open Subsurface Drainage System

At Pathareddy palem drainage pilot area, the open subsurface drainage system with drain spacing of 60-80 m and 0.25-0.35 m depth was laid out in an area of 22.3 ha for leaching out the salts instantly in order to grow the crop without any hindrance. As per the planned layout (Fig. 3), the system consists of 10 laterals covering a length of 1250 m and bottom width of 0.75 m with slope of 0.01% gradient being properly dugged out with hydraulic excavator. These laterals were connected to a collector drain, to a secondary drain and then to the Mutluru side drain to convey drain water offsite. Eight observation wells were installed up to 3.4 m depth in Mutluru channel command and four out of eight falls in the experimental site (Fig 2) to monitor water table fluctuations and for sampling ground water for water quality determinations.

Figure 3. Map showing Open sub surface drainage system at Pathereddy Palem drainage pilot area under Mutluru Channel Command of Krishna Western Delta

RESULTS AND DISCUSSION

Assessment of Soil pH and ECe

The results of the soil samples collected during the summer of 2005 indicated that pH in surface soils varied from 7.5 to 8.2 and ECe varied from 1.6 to 61.3 dS/m, mean of 20.8 dS/m. The salt concentration increased with increase in depth. Among the cations, sodium is dominant followed by magnesium, calcium and potassium. Among the anions, chlorides are dominant followed by sulphate and bicarbonate. The SAR of the soils varied from 0.98 to 41.8 (m moles/l)$^{1/2}$. Out of the sixty two soil samples, analysed for salinity, four soil samples are non saline (<4 dS/m), 12 soil samples are slightly saline (4-8 dS/m), 15 soil samples are moderately saline (8-16 dS/m) and 31 soil samples are strongly saline (> 16 dS/m). The soils of the drainage pilot area are considered as highly saline.

Results of the surface soil samples collected during the summer of 2006 recorded pH from 6.7 to 8.3 and ECe from 1.2 to 43.2 dS/m, mean of 11.6 dS/m. Out of the sixty two soil samples, 17 soil samples are non saline (<4 dS/m), 10 soil samples are slightly saline (4-8 dS/m), 19 soil samples are moderately saline (8-16 dS/m) and 16 soil samples are strongly saline (> 16 dS/m). The soils of the drainage pilot area are considered as highly saline. Figures 4 and 5 plots the percent distribution of saline soils in summer 2005 and summer 2006, respectively. They show that non saline soils increased from 6 to 29%.

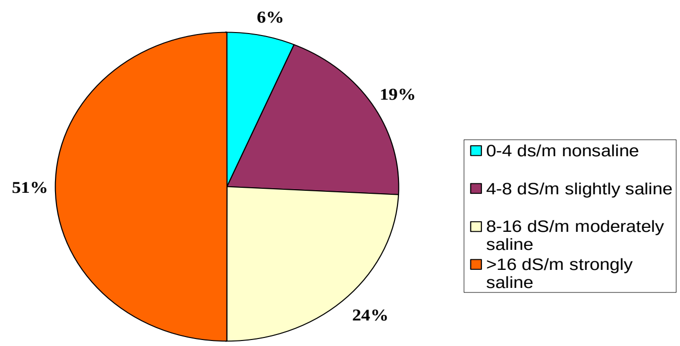


Figure 4. Percent distribution of saline soils of Pathareddy Palem in summer 2005

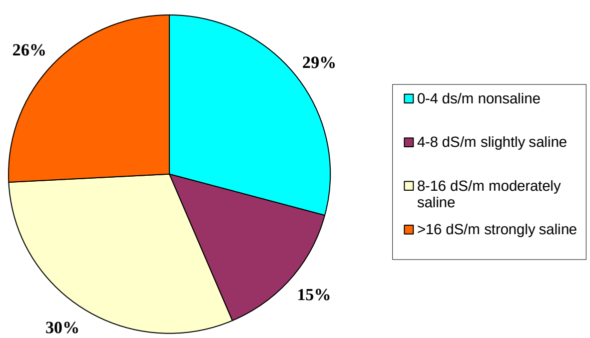


Figure 5. Percent distribution of saline soils of Pathareddy Palem in summer 2006

Figures 6 and 7 give contour maps of pH for summer 2005 and summer 2006, respectively, showing some shifting in pH.

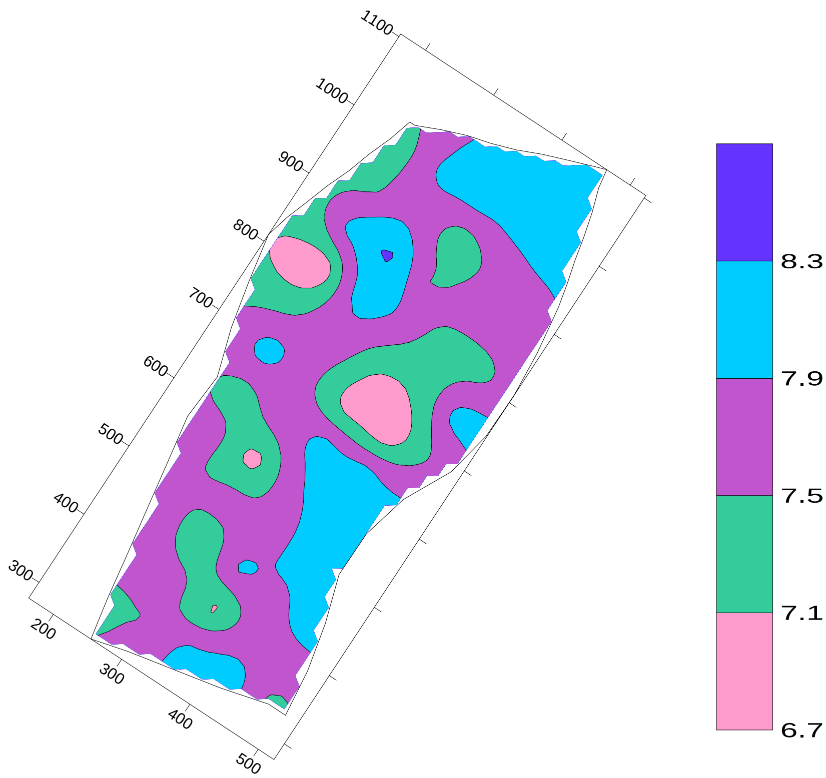


Figure 6. pH contour map of Pathareddy Palem drainage pilot area during summer, 2005

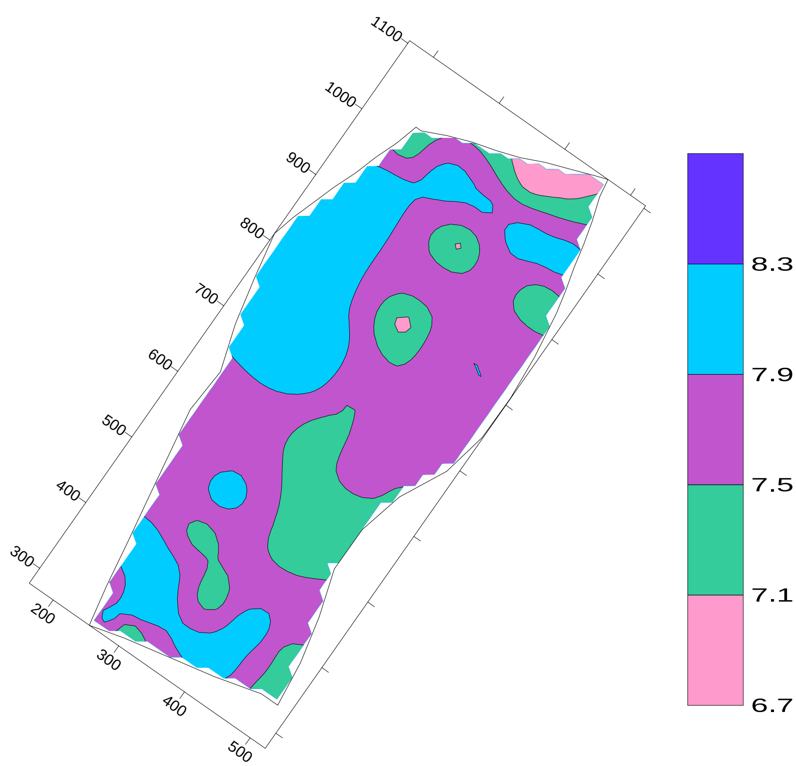


Figure 7. pH Contour map of Pathreddy Palem drainage pilot area during summer, 2006

Figures 8 and 9 present contour maps of ECe of surface soils for the summer 2005 and summer 2006, respectively, showing significant decreases in soil salinity.

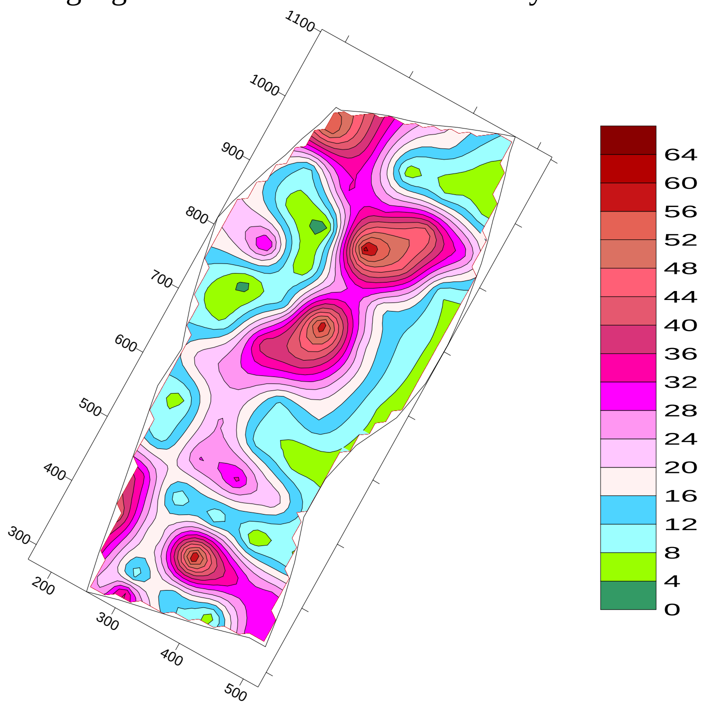


Figure 8. ECe Contour map of surface soils at Pathareddy Palem drainage pilot area during summer 2005

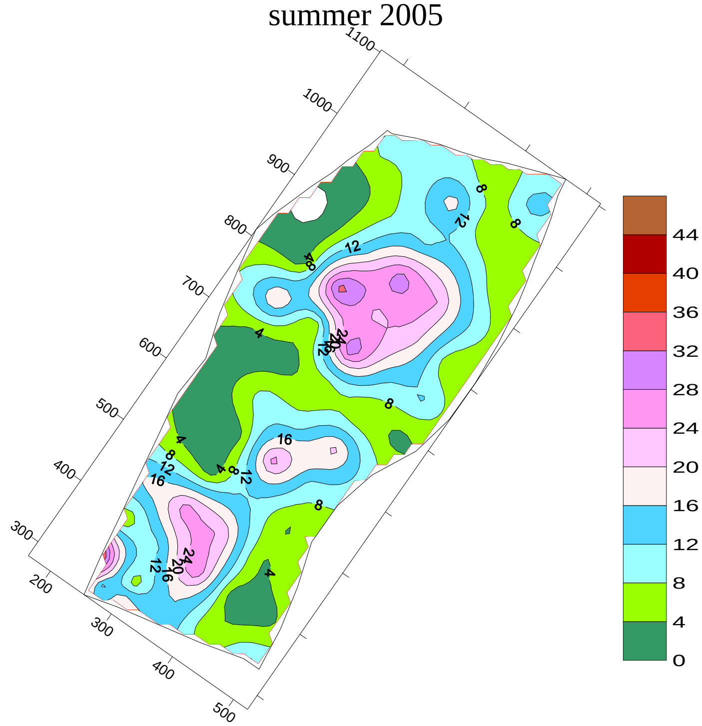


Figure 9. ECe contour map of surface soils at Pathareddy Palem drainage pilot area during summer 2006

Soil Profile Study.

Four soil profiles were dug in the middle and tail reaches of Mutluru Channel command and analyzed for ECe (dS/m) at different depths. It was observed that in the profiles ECe varied from 24 to 53 dS/m indicating the high salinity (e.g., Fig.10). In the profile at tail reach the high salinity was noticed at lower depths i.e., beyond 85 cm. The EC in ground water in these profiles varied from 24 to 38 dS/m and was considered as highly saline.

Soil depth	ECe (dS/m)
0-12	53
12-51	38
51-82	45
82-118	47
118+	39

ECe: 38 dS/m

Figure 10. Soil profile and its salinity at Kovelamudi (Middle Reach)

Soil Texture Analysis

About 27 soil samples were collected from the head, middle and tail reaches and analyzed for texture in the Mutluru Channel command. It was found that the soils are predominantly clayey in texture. The mean values were 26% sand, 22% silt and 51% clay (Table 1). The high clay percentage in the soil profile causes the soil to be of low infiltration capacity, poor internal drainage, low drainable porosity, low permeability etc. Low drainable porosity creates high fluctuations in the subsurface ground water levels. It will also result in high moisture holding capacity of such soil. Due to low infiltration rate of heavy textured soil it creates problem during leaching process for the reduction of the root zone salinity of the soils. However the open subsurface drainage system helped in reducing the salts below root zone and increased the crop yields. Similar results were also reported by AICRIP saline water at Bapatla (Annual reports of AICRP 2002-2006) in heavy textured soils. A general view of the cracking clay soils is depicted in Figure 11.

Table 1. Texture of soil samples of Mutluru Pilot area (27 samples)

Item	Sand (%)	Silt (%)	Clay (%)	Soil texture
Range	19.6 to 34.7	17.0 to 24.0	46.0 to 55.4	Clayey
Mean	26.25	22.16	51.45	

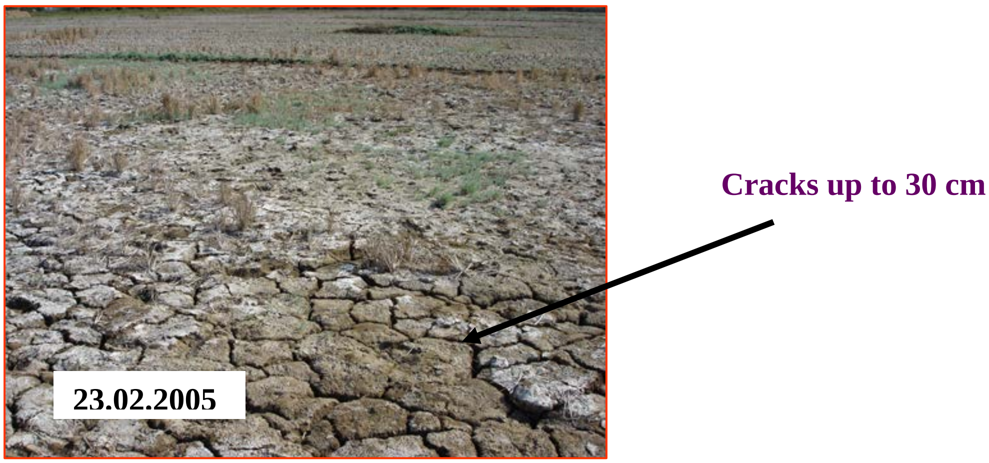


Figure 11. General view of the cracking clay soils in Mutluru pilot area

Status of Major Nutrients.

The available N, P_2O_5 and K_2O content of the surface soils varied from 188 to 440, 30 to 80 and 235 to 886 kg/ha, respectively. The status of nitrogen was low (< 250 kg/ha) in 28 soil samples and medium (250-500kg/ha) in 34 samples. The P status was low in one sample, medium (20-50 kg/ha) in 39 and was high (>50 kg/ha) in 22 samples. The status of K was high (>340 kg/ha) in all the samples. The average values of N, P_2O_5 and K_2O are 288, 54.7 and 444.8 kg/ha, respectively for the soils of the pilot area (Table 2).

Table 2. Available nutrient status in surface soil samples (0-15cm) of drainage pilot area

	Available Nutrient status (kg ha^{-1})		
	Nitrogen	Phosphorus	Potassium
Range	234 – 365	25 - 82	345 – 495
Mean	288.2	54.7	444.8

Micronutrient Status

Sixty two surface soil samples of the drainage pilot area were analyzed for available micronutrients, i.e., Fe, Mn, Cu and Zn (Table 3). The contents of Fe, Mn, Cu and Zn varied from 3.9 to 32.8, 1.16 to 23.2, 1.67 to 4.72 and 0.09 to 1.47 mg/kg, respectively. It was observed that 6, 10 and 56 samples were deficient in Fe, Mn and Zn respectively.

Table 3. Micronutrient status in surface soil samples (62) of drainage pilot area

	Fe	**Mn**	**Cu**	**Zn**
Range (mg/kg)	3.9-32.8	1.16-23.2	1.67-4.72	0.09-1.47
Critical level (mg/kg)	5.0	3.0	0.30	0.70
No.of samples deficient	6	10	-	56

Assessment of Ground Water Lowering

In order to monitor the groundwater fluctuations at the drainage pilot area and Mutluru channel command, eight observation wells were installed during November 2004 to a depth of 3.4 m. The depths of the water table were measured daily. Data indicated that the groundwater table was near the ground surface during the month of September 2005 due to heavy rains received during that period (381 mm). On the whole the average depth to water table was found to be 118 cm, 132 cm and 102 cm below ground level in the pilot area, middle and tail reaches, respectively, of the command area. The water table depth gradually increased from first fortnight (two weeks) of December to first fortnight of August and thereafter started rising due to onset of monsoon and irrigation to the paddy fields.

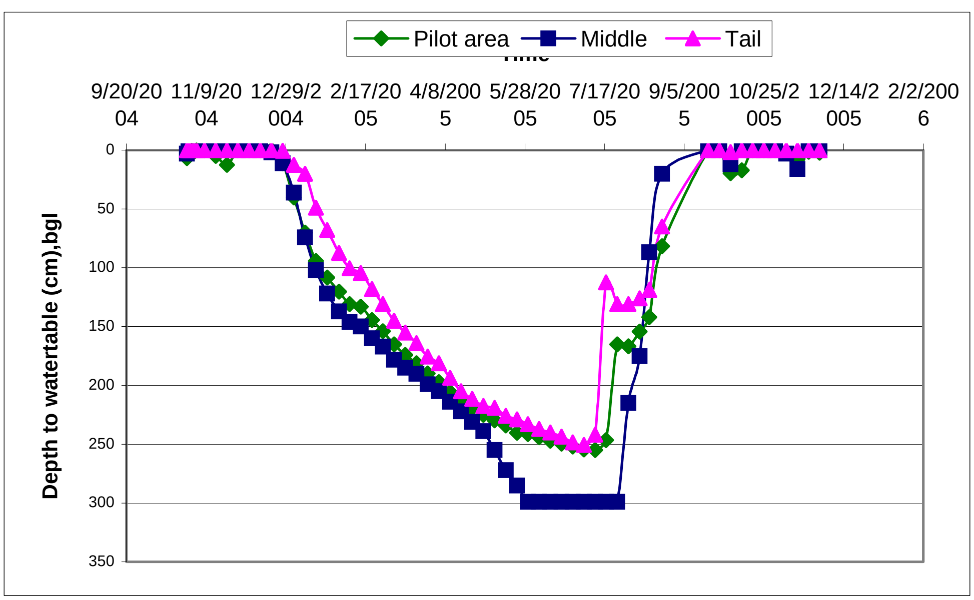


Figure 12. Ground water fluctuations in the Mutluru channel command during 2004-05

Ground Water Quality

Eight observation wells were installed in Mutluru pilot area. The water samples were collected from the observation wells at weekly intervals from September 2004 to July, 2006 for pH, EC, and SAR. The pH values varied from 6.9 to 7.9, EC from 18 to 44 dSm^{-1} and SAR from 18.5 to 53.3 $(m\ mole/l)^{1/2}$,respectively, recording lower values during monsoon season and higher values during summer period. The EC and pH in observation wells were higher during July –September, 2005 compared to same period during 2006 which may be due to failure of the monsoon (Figs. 13 and 14). The ground water is highly saline in nature and is not fit for irrigation to crops.

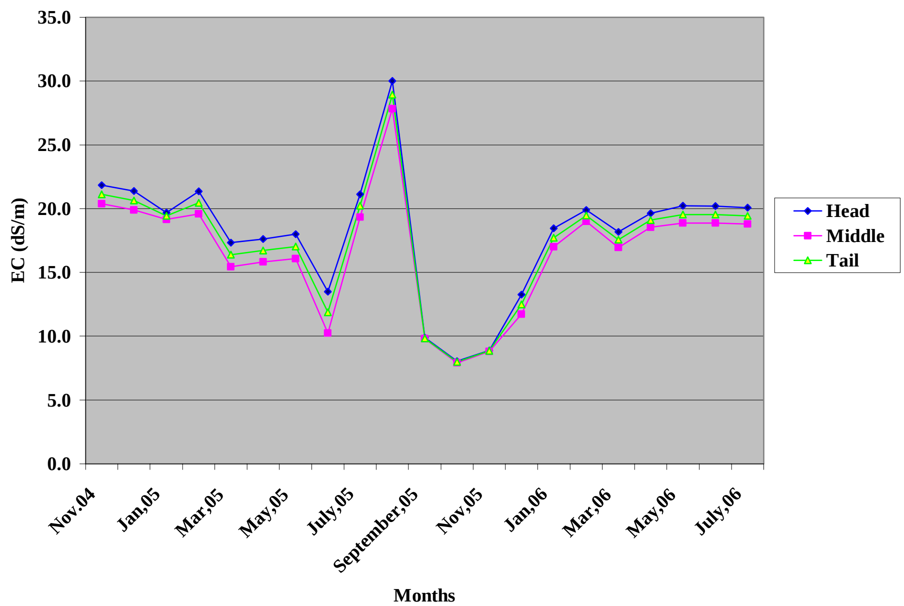


Figure 13. EC in observation wells of Mutluru Channel Command at head, middle and tail areas

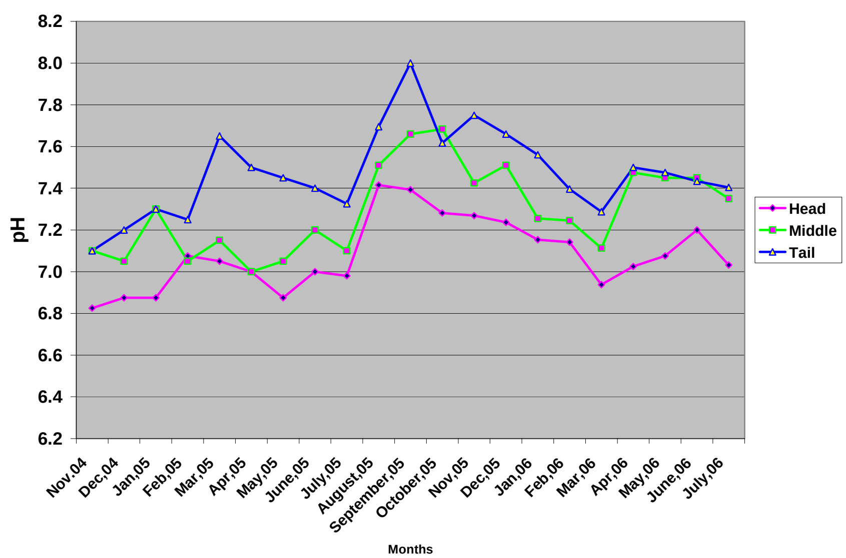


Figure 14. pH in observation wells of Mutluru Channel Command at head, middle and tail areas

Crop Yield.

Crop cutting experiments were conducted in one square meter area at all 62 grid points located in the Open Sub Surface Drainage (OSSD) pilot area during kharif 2005 and 2006. The average grain yields obtained during kharif 2005 and 2006 were 2.9 t ha^{-1} and 3.8 t ha^{-1}, respectively, indicating an increase of 0.7 t ha^{-1} (32 %) in the first year and 1.6 t ha^{-1} (73%) by the end of the second year after installation of OSSD system when compared to pre-drainage conditions (2.2 t/ha). Further the data on grain yield and salinity at 62 gird locations showed a relative decrease in soil salinity during post drainage conditions ranging from 1.2 to 43.2 dS/m with an average mean value of 11.6 dS/m as compared to average value of 20.2 dS/m in pre-drainage condition, which helped in increasing the grain yield.

However at certain grid locations increase in grain yield was observed in spite of higher soil salinity which may be attributed to low lying areas having sufficient water during crop growth period enabled to dilute the salt in irrigation water which might helped the crop to put forth good growth and there by increasing grain yield

CONCLUSION

Functioning of Open Sub Surface Drainage (OSSD) System installed in the pilot area of Mutluru Channel Command lowered the water table depth and decreased the soil ECe resulting in an increase in grain yield by 73% during the second year. These results confirm similar results obtained by Indo-Dutch Project under OSSD installed at Uppugundur pilot area during the year 1999 (IDNP Comprehensive Report**)**. The Open Sub-surface Drainage System needs frequent de-silting of drains during summer months of every year for effective functioning of the system. Such rehabilitation requires a huge amount of labor work. No doubt converting salt affected lands to cultivable lands could easily fetch good returns to beneficiaries. Thus, it is very clear that there are benefits by installing the OSSD in water logged and saline land in the Krishna Western Delta Command.

REFERENCES

Annual reports 2002-2006, All India Co-ordinated Project on management of salt affected soils and use of saline water in Agriculture**.**

Black, C.A.(1965). Methods of Soil Analysis, Part-1 &II American Society of Agronomy Madison, Wisconsin, USA.

Comprehensive Report on Research Achievements of Indo-Dutch Net Work Project, Bapatla (1-4-96 to 31-3-2002) on "Drainage and Water Management for Salinity Control in Canal Commands".

Rachards, L. A. (1954). Diagnosis and Improvement of Saline and Alkali Soils. USDA Handbook 60, US Department of Agriculture and Oxford & IBH Pub. Co. Pvt. Ltd., New Delhi.

PROVIDING RECYCLED WATER FOR CROP IRRIGATION AND OTHER USES IN GILROY, CALIFORNIA

Craig J. Smith, P.E.[1]
Benjamin R. Herston, P.E.[2]
Saeid Vaziry, P.E.[3]

ABSTRACT

The South County Regional Wastewater Authority (SCRWA) delivers recycled water to local farmers, golf courses and parks throughout the City of Gilroy, California, located approximately 30 miles south of San Jose, California. The SCRWA recently completed an expansion to the tertiary treatment system, which included additional tertiary filter banks, a new storage reservoir, additional pumping capacity, and a new delivery pipe with turnouts.

With the new facilities on-line, the SCRWA recycled water system consists of 6 million gallons per day of firm tertiary filtration capacity, one on-site recycled water storage reservoirs with a total of 3 million gallons of storage, two recycled water delivery pipelines, and four pumping stations.

The new 3 MG reservoir and additional pumping stations at the SCRWA treatment plant are critical in meeting the peak demands of agricultural irrigation. The reservoir enables the treatment plant operators to shave demand peaks and provides the flexibility for the SCRWA to shut down tertiary filters as needed. Having 6 MGD of firm tertiary filter capacity gives the SCRWA the capability of producing enough recycled water to meet existing and future demands.

Interest among potential agricultural recycled water users in the Valley is growing as the price for recycled water becomes competitive with the price of pumping groundwater in the area. Farmers see recycled water as an economical and reliable source for crop irrigation. The SCRWA recycled water system has proven to be an excellent source of high quality water for irrigation of farmlands.

INTRODUCTION

The South County Regional Wastewater Authority (SCRWA) is a joint powers authority between the Cities of Gilroy and Morgan Hill, California, established to treat wastewater for the South Santa Clara County region. The SCRWA owns and operates a conventional secondary wastewater treatment plant and a co-located reclamation facility in Gilroy, California, approximately 30 miles south of San Jose, California, as shown in Figure 1. The two cities are

[1]Senior Project Manager, URS Corporation, 1333 Broadway, Suite 800, Oakland, CA 94612
craig_smith@urscorp.com
[2]Senior Engineer, MWH Americas, Inc., 1340 Treat Blvd., Suite 300, Walnut Creek, CA 94596
benjamin.r.herson@mhwglobal.com
[3]Chief Environmental Engineer, South County Regional Wastewater Authority, 1500 Southside Drive, Gilroy, CA 95020 Saeid.Vaziry@ci.gilroy.ca.us

predominantly residential communities with a total population served by the SCRWA of approximately 90,000 people.

Agricultural lands surround both communities, and is the predominate landuse for the area. This farming region is known as the Pajaro Valley and is ranked fifth in agriculture production in California. The climate for the valley is semiarid, so water supply is an important issue for farmers in the region. The Pajaro Valley gets most of its water from pumping groundwater and importing water from other parts of California. Recycled water provides a small but growing portion of the water used for agriculture in the region. As the cost of potable and well water increases, the beneficial use of recycled water becomes more evident.

Figure 1. Vicinity Map

The recycled water program at the SCRWA is operated in partnership with the Santa Clara Valley Water District (SCVWD). The SCRWA produces the tertiary treated water at the treatment facility and the SCVWD distributes the water as a wholesaler through its distribution system. Both agencies work together to promote the use of recycled water by agricultural, commercial and industrial users throughout the region.

The SCRWA and the SCVWD recently completed construction of a project to expand the recycled water facilities. The project components included increasing the firm capacity of the tertiary filters from 3 million gallons per day (MGD) to 6 MGD, installing a 3 MG treated water reservoir, two new pump stations, a new 20-inch delivery pipeline, four new irrigation turnouts, and upgrades to the reclamation plant controls systems. These new upgrades provide the SCRWA with the flexibility to better meet the needs of agricultural, commercial and industrial users throughout the system.

This paper will discuss the recycled water program at the SCRWA, including the water reclamation facility with newly constructed improvements, the new storage reservoir, the delivery system including irrigation turnouts, permit requirements including inspection and end user training, and special requirements of agricultural users.

THE SCRWA'S WATER RECLAMATION FACILITY

Facility Description

The SCRWA secondary wastewater treatment plant is an 8.5 MGD conventional facility built in 1994. The plant includes a headworks with bar screens and grit removal followed by pre anoxic tanks for nitrification. Mixed liquor then flows to two oxidation ditches employing mechanical aerators, followed by secondary clarifiers. Secondary effluent is directed to approximately 400 acres of percolation ponds for disposal. Sludge is dewatered using belt presses and used as daily cover at a local landfill.

Co-located with the secondary treatment facility, the SCRWA reclamation plant was constructed in 1995 and utilizes anthracite media filters to tertiary treat a portion of the secondary effluent to meet California's Title 22 Water Reuse Criteria. The facility also includes a chlorine contact basin, a dechlorination facility, and distribution pumping stations. The original pre-design report for the reclamation facilities recommended a phased construction approach such that expansion would be staged to an ultimate firm capacity of 12 MGD. The configuration at ultimate capacity included 5 filters (each having a 3 MGD capacity), such that 12 MGD reliable capacity can be produced with one filter out of service for backwash or maintenance (MWH, 1992). The original reclamation facility constructed in 1995 included the following facilities:

- Two anthracite granular media filters (reliable capacity of 3 MGD)
- Filter feed pumping facility (reliable capacity of 4 MGD)
- Filter support systems (backwash and chemical feed system)
- Disinfection (chlorine contact basin with 8.5 MGD capacity)
- Southwest Reclamation Pump Station (2 MGD capacity)

As recycled water demands increased, the SCRWA elected to expand the reclamation facility. Initially the objective was to increase the reliable tertiary filtration capacity to 6 MGD by adding one additional anthracite media filter cell. However, based on the paired layout of the existing filters and increased construction costs for a single filter, it was determined that construction of two filters (i.e., providing additional 6 MGD of capacity) was more cost effective. Therefore under the expansion project, the filtration capacity at the SCRWA reclamation facility was expanded by 6 MGD to a total reliable filtration capacity of 9 MGD. However, expansion of the filter support systems and chemical feed systems remains at the target 6 MGD capacity. These facilities can be further expanded during a future plant upgrade project. Construction of the new facilities was completed in 2006. The new reclamation facility constructed in 2006 included the following facilities:

- Two new anthracite granular media filters (additional capacity of 6 MGD)
- Filter feed pumping facility (additional capacity for 2 MGD)
- Filter support systems (additional backwash and chemical feed capacity for 3 MGD)
- Southwest Reclamation Pump Station (additional 2 MGD capacity)
- New Reclaimed Water Pump Station (3 MGD capacity)
- New 1 mile 20-inch South Pipeline for recycled water delivery (includes 4 turnouts)
- New on-site storage reservoir (3 MG)

- New Reservoir Return Pump Station (3 MGD capacity)

The SCRWA facility is shown in Figure 2 below.

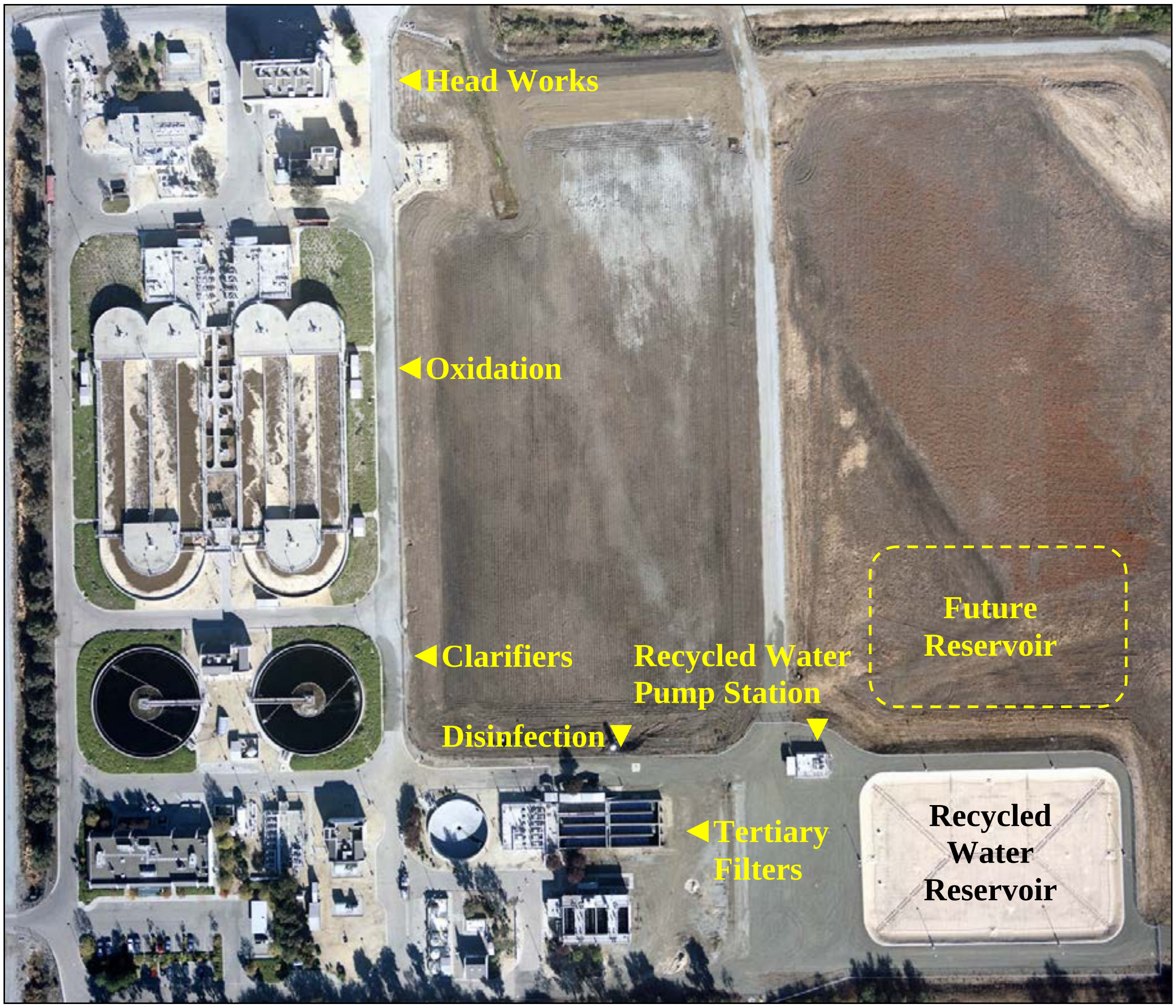


Figure 2. SCRWA Facility

Planned Facility Improvements

The SCRWA is currently in the process of designing a new ultraviolet (UV) disinfection facility to disinfect tertiary treated water for recycled water delivery during the summer months and discharge to the Pajaro River during the winter months. The UV facility will be constructed in 2008 and have an initial capacity of 4.5 MGD, with accommodations to expand to 13 MGD. The UV facility will provide disinfection of the tertiary treated water using the latest proven technology while eliminating disinfection bi-products related to chlorination such as dibromochloromethane ($CHBr_2Cl$) and bromodichloromethane ($CHBrCl_2$). Although these chlorination bi-products are not known to cause adverse health effects in people, animal studies show that high concentrations can damage the liver and kidneys and affect the brain (ATSDR 1999).

The SCRWA is also in the process of extending the South Pipeline an additional 2 miles to provide recycled water to farmers south of the Facility during the summer months and for discharge of tertiary treated water to the Pajaro River during the winter months. Four to six new turnouts will be installed along the new pipeline reach to provide water to new users. The pipeline with new turnouts will be constructed in 2008.

The SCRWA maintains a continuous improvement program at the facility. They are diligent in evaluating all of the latest treatment technologies and consulting with experts in the field of water treatment, civil/mechanical engineering and operations and maintenance specialists.

THE SCRWA'S ON-SITE STORAGE RESERVOIR

Reservoir Design

As part of the Filter Expansion Project constructed in 2006, the SCRWA constructed a new 3 MG on-site storage reservoir to provide additional flexibility and reliability for their recycled water delivery system. To be consistent with the capacity of the tertiary treatment facilities, provisions were made for 6 MG of recycled water storage. A two-cell, 6-MG storage reservoir was designed, but only one, 3 MG cell will be constructed as a part of the Filter Expansion Project. The second cell will be constructed when recycled water demands increase enough to necessitate more storage capacity (see Figure 1).

The reservoir site was graded to raise the water surface elevation to 162.5 feet. This prevented the overflow of the pond. The reservoir has a Hypalon® membrane liner and floating cover. The cover design is illustrated in Figure 3, and an as-built photo is provided in Figure 4. The design criteria for this new recycled water storage reservoir are summarized in Table 1.

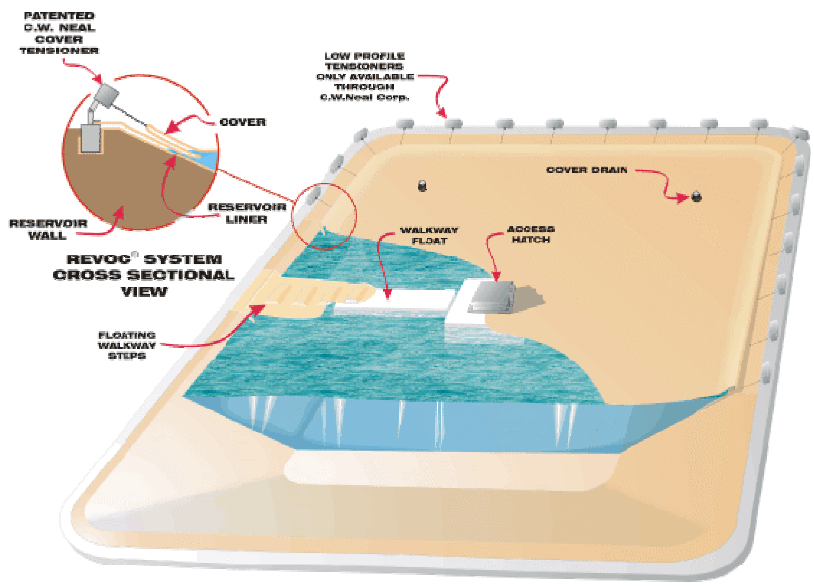


Figure 3. Schematic of Hypalon® Membrane Liner and Floating Cover System (CW Neal 2007)

Figure 4. Photograph of Final Constructed Reservoir

Table 1. Design Criteria for New Recycled Water Storage Reservoir

Storage capacity	6 MG
Total number of cells	2
Number of cells constructed	1
Total pond depth	14.5 ft
Freeboard height	2 ft
Maximum water depth	12.5 ft
Minimum water depth	1 ft
Footprint (each cell)	41,000 ft^2
Lining	Hypalon membrane
Cover	Hypalon floating cover

Reservoir Operation

A new Reservoir Return Pump Station facilitates two-way transport of recycled water in and out of the reservoir. In one direction, recycled water is transported from the chlorine contact basin to the new recycled water reservoir, via a new 30-inch fill line. In the other direction, recycled water from the same reservoir is transported, via a new 30-inch withdraw line, to the Reservoir Return Pump Station that pumps to the Reclaimed Water Pump Station wet well for conveyance to end users. Table 2 provides a summary of the design criteria for the new Reservoir Return Pump Station.

Table 2. Design Criteria for New Reservoir Return Pump Station

Number of units (b/o), total	4
Number of units, standby	1
Number of units, installed	2
Type	Vertical Turbine
Capacity, each unit	2100 gpm (3 mgd)
TDH	14 ft
Motor Size (each)	15 HP

The new on-site reservoir is used to store water during periods of low demand and deliver additional water during periods of high demand (higher than the flow out of the filters). The reservoir gives the SCRWA flexibility to deliver recycled water at high rates on-demand, and increases the reliability of the recycled water supply by providing storage reserves in case of a reclamation plant shut-down.

The reservoir is crucial in the delivery of water to agricultural users throughout the recycled water delivery system. Agricultural users in the Pajaro Valley arid climate tend to require large quantities of water on-demand and cannot be without water for extended periods of time during the growing season. The reservoir allows the SCRWA to balance the peaks of high volume on-demand water use and provide farmers with a reliable source of clean water throughout the growing season.

NEW RECLAMATION PUMP STATION AND DELIVERY SYSTEM

The new Reclaimed Water Pump Station pumps water to agricultural lands south of the SCRWA reclamation facility. The pump station can pull water from two sources: 1) the chlorine contact chamber effluent; and 2) the reservoir storage water provided by the Reservoir Return Pump Station. A schematic of the reclaimed water treatment storage and delivery system is shown in Figure 5.

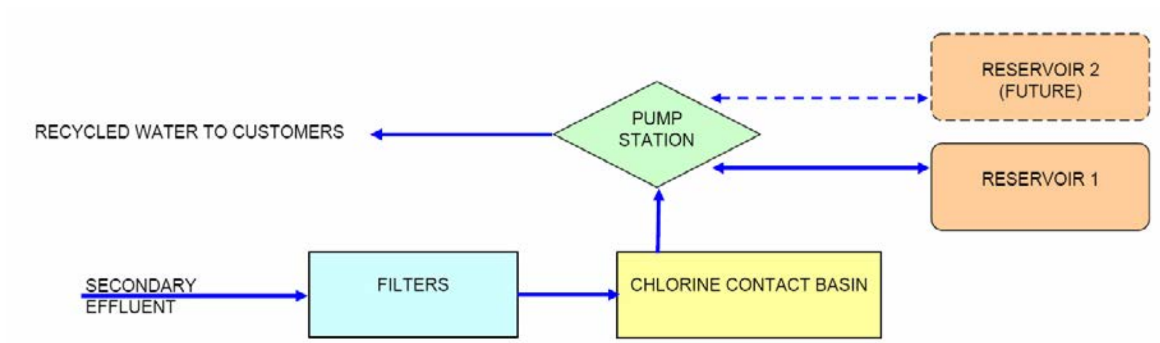


Figure 5**.** Treatment, Storage and Delivery Schematic

The Reclaimed Water Pump Station utilizes the new 20-inch South Pipeline to deliver recycled water for irrigation. The pump station includes 2 vertical turbine pumps run on variable frequency drives in a lead/lag configuration to deliver water to recycled water users at 80 psi. The pumps pump against a pressure sustaining valve to regulate pressure in the South Pipeline. This pumping configuration provides agricultural users with recycled water at a constant pressure for irrigation of crops. Design Criteria for the pump station are provided in Table 3.

Table 3. Design Criteria for New Recycled Water Pump Station

Number of units (b/o), total	3
Number of units, standby	0
Number of units, installed	2
Type	Vertical Turbine
Capacity, each unit	2100 gpm (3 mgd)
TDH	170 ft
Motor size (each)	125 HP

Though there are some agricultural users and potential users located off of the 12-inch Southwest Reclamation Pump Station recycled water pipeline, the Reclaimed Water Pump Station and South Pipeline provide recycled water to the majority of the SCRWA's agricultural users. Extension of the South Pipeline to the Pajaro River will deliver recycled water to many more agricultural users in the Pajaro Valley.

The constructed portion of the South Pipeline includes four connection points (turnouts) for agricultural users to hook up irrigation systems along the pipeline. An additional four more turnouts are planned when the pipeline is extended. The turnouts are approximately 1000 feet apart and are evenly spaced along the alignment. The turnouts contain protection devices including check valves and pressure regulators to insure no contamination of the recycled water. The turnouts have a standard blind flange for agricultural users to easily connect their existing irrigation equipment. Each of the turnouts is properly painted and marked in English and Spanish to notify users of the product. A photograph of a turnout on the South Pipeline is shown in Figure 6.

Figure 6. Irrigation Turnout on the South Pipeline

THE SCRWA'S WATER RECLAMATION FACILITY PERFORMANCE

Clean Water Treatment Process

Clean water produced at the SCRWA follows criteria of the California Regional Water Quality Control Board and the California Department of Health Services. These regulatory agencies set treatment standards for wastewater treatment and recycled water use respectively. Specifically, California's Title 22 sets water reuse criteria, and is listed in Table 4 (CDHS 2001).

Table 4**.** California's Title 22 Criteria for Recycled Water with Granular Media Filtration and Chlorine Disinfection

Maximum filter loading rate	5 gpm/sf
Daily average turbidity	< 2 NTU
24-hour turbidity	< 5 NTU 95% of the time
Maximum turbidity	10 NTU
Contact time (CT)	> 450 mg-min/l
Total coliform (7 day)	< MPN of 2.2 per 100 ml
Total coliform (30 day)	< MPN of 23 per 100 ml

Each treatment plant receives different water quality; therefore treatment processes must be developed site specific. At SCRWA, granular anthracite media filters and disinfection are used to produce tertiary effluent. The SCRWA reclamation facility exceeds the California Title 22 requirements for recycled water treatment using granular media filtration. Table 5 provides a summary of reclamation facility treatment performance from 2003 to present.

Table 5**.** Reclamation Facility Performance – Summary of Data (MWH 2006a)

Daily average flow winter (November – April) Summer (May – October)	0.25 MGD 1 – 1.5 MGD
Daily maximum flow winter (November – April) Summer (May – October)	2 MGD 3 MGD
Average TSS filter influent	4.5 mg/L
Average TSS filter effluent	<1 mg/L
Daily average influent turbidity	1.4 NTU
Daily average effluent turbidity	0.4 NTU
Daily average effluent BOD	2 mg/l
Daily average effluent nitrate as nitrogen	2.3 mg/l
Daily average effluent dissolved oxygen	5 mg/l
Effluent coliform	2 MPN/100
Average solids loading prior to backwash)	40 pounds

Recycled water is safe to use. Potential health risks associated with the use of recycled water have been well documented nationwide as water recycling projects are implemented and carefully monitored by responsible local health authorities and water quality control agencies. Tertiary recycled water is a highly treated, filtered and disinfected product according to the California Department of Health Services criteria. These standards for recycled water are among the most stringent in the world. No health-related problems have been traced to any of the recycling projects currently operating in California. (SCRWA 2006) As shown in Table 6, recycled water is at SCRWA is of comparable or better quality than the local shallow groundwater for many constituents.

Table 6**.** Comparison of SCRWA Recycled Water Quality to Local Groundwater (SCRWA 2006)

Irrigation Water Quality Comparison				
Constituent	Units	SCRWA-SCVWD Recycled Water	Gilroy Muni. Deep Ground Water (Well MW-10)	Gilroy Shallow Ground Water (at SCRWA Facility)
Total Dissolved Solids	mg/L	582	400	650
Boron	mg/L	0.14	0.1	0.35
Calcium	mg/L	43	120	170
Chloride	mg/L	144	33	120
Magnesium	mg/L	27	18	25
Sodium	mg/L	99	37	110
Sulfate	mg/L	57	110	120
Nitrogen:				
Nitrate-Nitrogen	mg/L	2.3	5	10
Nitrite-Nitrogen	mg/L	0.03	2	0.05
ph	Std. Units	7.6	7.3	6.9

Note: Water quality data from 2004-05 period.

Annual Operational Conditions

The historical data indicates that the hydraulic loading rate to the filters varies seasonally. The daily average flow to the filters in the winter months (November through April) is 0.25 MGD, ranging from 0.1 MGD to 2 MGD, and the daily average flow to the filters during summer months (May through October) is between 1 and 1.5 MGD, while the minimum and maximum flows ranged from 0.2 MGD to 3.5 MGD. The SCRWA currently sends the secondary effluent to all four filters, and only takes one off-line during backwash.

With the new 3 MG storage reservoir and new Reclaimed Water Pump Station with variable frequency drives in operation, the erratic water demands of agricultural recycled water users can be accommodated. The performance of the SCRWA reclamation facility has drastically improved with the new facilities on-line. As shown in Figure 7, recycled water demand at the Reclaimed Water Pump Station and South Pipeline reflect the nature of agricultural use of recycled water. Recycled water flow demands of up to 2,200 gpm were seen in spring 2007. Farmers tend to take large quantities of water on-demand for short periods of time. The SCRWA system was designed and is operated to accommodate these demands.

Most of the agricultural irrigation systems on the south pipeline use full circle impact sprinklers, requiring a working pressure between 40 and 80 psi. Each sprinkler head is capable of delivering flows between 20 and 100 gpm, depending on the make and model. Farmers can be using 50 to 100 sprinkler heads each time they irrigate their field, so demand is very high during periods of use. The SCRWA treatment and delivery system is designed to accommodate these agricultural demands, and as such, demand for the SCRWA's recycled water among the agricultural community is growing.

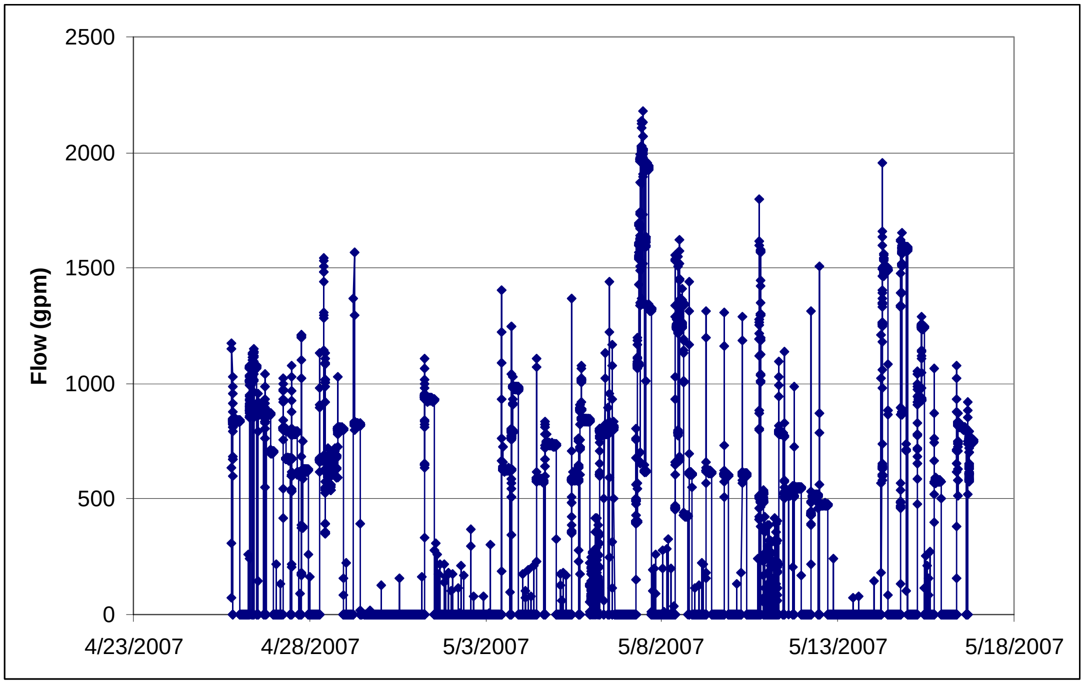


Figure 7. Recycled Water Demand at the South Pipeline
April 25 – May 16, 2007

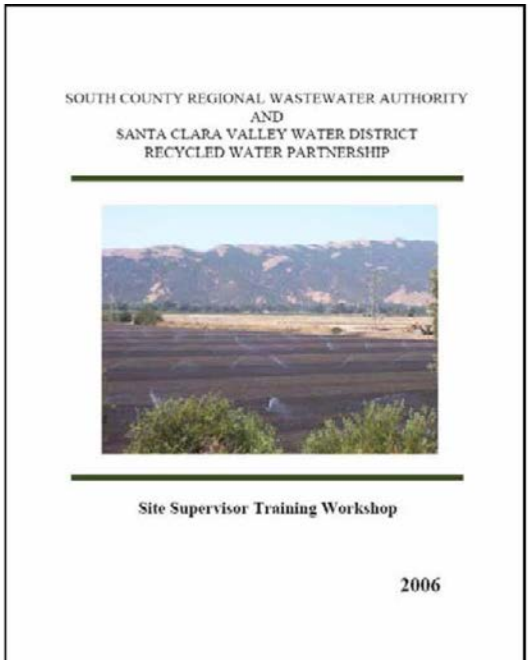
RECYCLED WATER USE PERMITS AND TRAINING

In accordance with the SCRWA's Waste Discharge Requirements and California Title 22 regulations, all recycled water users must designate a "Site Supervisor" and the Site Supervisor is required to attend annual training sessions at the SCRWA. The Site Supervisor is the responsible party for sharing recycled water use requirements through their organization and is the keeper of all necessary documentation (CRWQCB 2004).

It is essential for Site Supervisors to provide training to agricultural workers on the importance of recycled water safety and proper use of the water. Due to the nature of their work, agricultural workers are often exposed to recycled water, and need to understand safety precautions that should be followed when using the product. The SCRWA provides Site Supervisors with a Site Supervisor Training Manual to share with workers and requires that Site Supervisors educate their workers on the proper uses of recycled water. The cover of the Training Manual is shown in Figure 5.

Proper documentation is the most important issue for the Site Supervisor, especially for agricultural users. Should a contamination issue arise, it will be imperative to confirm the configuration of the irrigation system (piping layout), maintenance and testing activities and the proper training and notification of all employees.

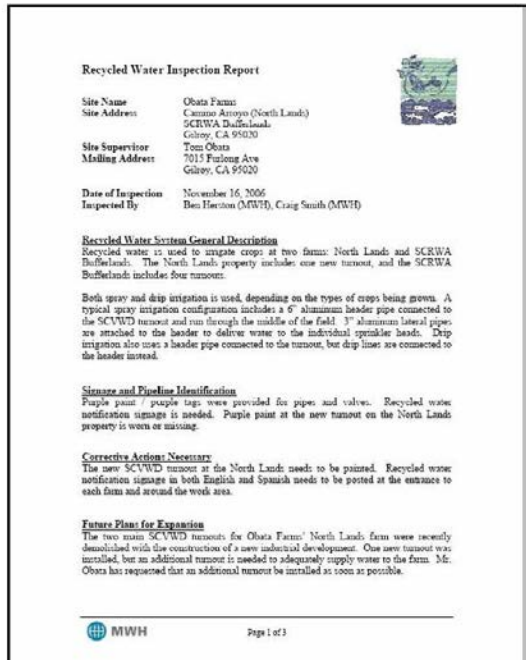
In addition to Site Supervisor training, the SCRWA visits all recycled water user facilities to inspect the connections and confirm separation from any other water systems. Site inspections are performed annually prior the renewal of the recycled water use permits. An example of a recycled water inspection is provided in Figure 8.



SOUTH COUNTY REGIONAL WASTEWATER AUTHORITY
AND
SANTA CLARA VALLEY WATER DISTRICT
RECYCLED WATER PARTNERSHIP

Site Supervisor Training Workshop

2006



Recycled Water Inspection Report

Site Name Obata Farms
Site Address Camino Arroyo (North Lands)
SCRWA Bufferlands
Gilroy, CA 95020
Site Supervisor Tom Obata
Mailing Address 7015 Furlong Ave
Gilroy, CA 95020

Date of Inspection November 16, 2006
Inspected By Ben Herston (MWH), Craig Smith (MWH)

Recycled Water System General Description
Recycled water is used to irrigate crops at two farms: North Lands and SCRWA Bufferlands. The North Lands property includes one new turnout, and the SCRWA Bufferlands includes four turnouts.

Both spray and drip irrigation is used, depending on the types of crops being grown. A typical spray irrigation configuration includes a 6" aluminum header pipe connected to the SCVWD turnout and run through the middle of the field. 3" aluminum lateral pipes are attached to the header to deliver water to the individual sprinkler heads. Drip irrigation also uses a header pipe connected to the turnout, but drip lines are connected to the header instead.

Signage and Pipeline Identification
Purple paint / purple tags were provided for pipes and valves. Recycled water notification signage is needed. Purple paint at the new turnout on the North Lands property is worn or missing.

Corrective Actions Necessary
The new SCVWD turnout at the North Lands needs to be painted. Recycled water notification signage in both English and Spanish needs to be posted at the entrance to each farm and around the work area.

Future Plans for Expansion
The two main SCVWD turnouts for Obata Farms' North Lands farm were recently demolished with the construction of a new industrial development. One new turnout was installed, but an additional turnout is needed to adequately supply water to the farm. Mr. Obata has requested that an additional turnout be installed as soon as possible.

MWH Page 1 of 3

Figure 8. Cover page from Recycled Water Users Training Handbook (MWH 2006b) and Sample Recycled Water Inspection Report

CONCLUSIONS

Through good planning, design and operations, the SCRWA has developed a recycled water program that can accommodate commercial, industrial and agricultural users. Agricultural users of the system have different requirements than commercial and industrial users, as their use is more seasonal and often requires high volumes of water on-demand. These users require high quality water delivered through a versatile storage and delivery system. The SCRWA is able to meet these agricultural demands by providing recycled water that exceeds California's Title 22 standards and is delivered by a versatile pumping station with variable frequency drives, a pipeline and turnouts with pressure sustaining valves and a storage reservoir to shave demand peaks. In addition, the SCRWA provides training to users and inspection of the users systems to ensure the recycled water is being used properly and there is no contamination of the recycled water.

While some consumers are enthusiastic about the use of recycled water, other consumers are concerned about food safety and water-borne diseases. This is understandable due to recent instances of vegetable contamination in California. However, no farms using recycled water have been identified as producing contaminated food. This is in large part to the good records kept by treatment facilities and their customers. The SCRWA and its agricultural customers follow strict and well established guidelines set by the California Department of Health Services to insure a quality product is being used in the field at all times.

California is an arid environment with a growing population and limited water resources. It is good public policy to develop recycled water as an alternative water resource. In time and with good practice, more consumers will realize the beneficial uses of recycled water. When the next drought hits California, as it surely will, SCRWA and other recycled water purveyors will help the local communities meet commercial, agricultural and residential water demands through smart use of valuable resources.

REFERENCES

Agency for Toxic Substances and Disease Registry (ATSDR), ToxFAQs for Dibromochloromethane and Bromodichloromethane. Atlanta: Centers for Disease Control, July 1999. http://www.atsdr.cdc.gov

California Department of Health Services, California Health Laws Related to Recycled Water "The Purple Book", Sacramento: California Department of Health Services, June 2001.

California Regional Water Quality Control Board Central Coast Region, Waste Discharge Requirements Order No. R3-2004-0099, NPDES No. CA0049964, WDID No. 3 430100001, San Luis Obispo: California Regional Water Quality Control Board, 2004.

C. W. Neal Corp., Conceptual Cut-Away View Drawing, www.cwneal.com, June 2007.

MWH, SCRWA 2005 Trend Report, Walnut Creek: MWH, May 2006.

MWH, South County Regional Wastewater Authority and Santa Clara Valley Water District Recycled Water Partnership Site Supervisor Training Workshop Manual, Walnut Creek: MWH, 2006.

MWH, Reclamation Facility Preliminary Design Report, Walnut Creek: MWH, 1992.

South County Regional Wastewater Authority (SCRWA) and Santa Clara Valley Water District Recycled Water Partnership, Site Supervisor Training Workshop Handbook, Gilroy:, South County Regional Wastewater Authority, 2006.

STATUS AND CONTROLLING RESEARCH OF NON-POINT SOURCE POLLUTION IN CHINA

Wang Shaoli[1]
Zheng Binghui[2]

ABSTRACT

Non-point source pollution has become an important factor affecting China's water environment quality, and the proportion of loading that is occupied by non-point source in the water environment pollution is increasingly rising. This paper introduces the status, main problems and causes of China's water environment quality, expounds main sources and characters of non-point source pollution, and the situation of controlling technologies. Taking Taihu lake region as example, the paper introduces the application and practices of controlling technology, analyzes the existing problems of controlling and management of non-point source pollution, and proposes some suggestions for future researches.

Key words: Water environment, Non-point source pollution, Controlling technology

INTRODUCTION

With the increase of human production activities and speedup of urbanization advancement, the available water resources are increasingly polluted, the pollutants, such as agricultural chemical substances, sewage and industrial wastewater without treatment or incomplete treatment, are severely affecting the situations of water quality, which aggravates the contradiction of supply and demand of water resources. In China, with the stepwise implementation of controlling measures for industrial point source pollution, the non-point source pollution has become an important pollutant affecting water environment quality due to larger incidence and difficult controlling. The components of pollution loading in the water bodies are producing the obvious change. The proportion of loading occupied by non-point source in the water environment pollution is increasingly rising, among which non-point source pollution produced by agricultural activities is the most prevalent and severe contaminant, and is being realized gradually by Chinese for its threats to environment. Compared with point source pollution, non-point source pollution has the characteristics of universality in space, uncertainty in time, wide-ranging harm, large difficulty in controlling and managing etc. If the pertinent polices and measures could not be timely studied and established, non-point source pollution will restrict severely the ultimate improvement of China's water environment quality.

[1]Professor, Department of irrigation and drainage, China Institute of Water resources and Hydropower Research, P.O.Box 366, Beijing 100044, P.R.China；shaoliw@iwhr.com
[2]Professor, China research academy of environmental sciences, Beijing, 100012; Zhengbh@craes.org.cn

STATUS AND CAUSES OF WATER ENVIRONMENT QUALITY

Status of Water Environment Quality

Water quality has been deteriorating in many rivers in China. Based on the nationwide investigation obtained by 411 cross sections of 7 major water systems in 2005, the ratio of class I I – III, class IV – V, and below class V in the surface water quality is 41%, 32% and 27% respectively (SEPAC,2005), among which the water quality is better in Pearl and Yangtze river systems, poor in Liao river, Huai river, Yellow river and Songhuajiang river systems, and severely polluted in Hai river system. The 54 percent of observed cross sections exceeds class V of the standard of surface water environment quality, seeing Figure 1. Major pollution indices are Ammonia Nitrogen (NH_4^+-N), Biochemical Oxygen Demand (BOD_5), Permanganate (K_2MnO_4) index and Petroleum. Generally speaking, the water quality is poor in the tributaries than in main rivers, poor in the lower stream of the rivers than in the upper stream of the rivers, better in South China than in North China, and better in Midwest area than in eastern developed area.

The lakes and reservoirs in China are also severely polluted, especially three major lakes (called “three lakes”), namely Taihu, Chaohu and Dianchi lakes, all exceed class V of the standard of the surface water environment quality. Total nitrogen (TN) and total phosphorus (TP) of major lakes and reservoirs are in the medium and high eutrophic state. Based on the investigation of 28 major lakes and reservoirs, the number of lakes and reservoirs belonging to class II, III, IV, V and below V are 2, 6, 3, 5 and 12, taking up 7%, 21%, 11%, 18% and 43% respectively, seeing Figure 2.

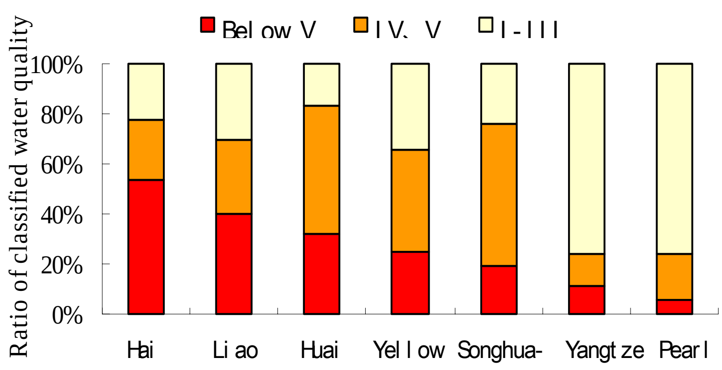


Figure 1. Ratio of water quality classification of 7 major water systems

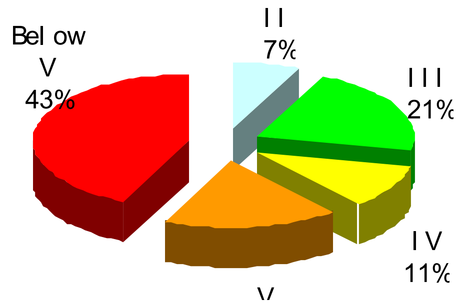


Figure 2. Ratio of water quality classification of lakes and reservoirs

A majority of sea area near the sea-shore has good water quality, but partial sea area is severely polluted. The seawater belonging to class I and II accounts for 67.2%, class III for 8.9%, class IV and below IV for 23.9%. Major contaminants are inorganic nitrogen and active phosphate.

Main Water Environment Problems And Causes

The water pollution has become dominating water environment problem in China, of which the outstanding problems are the eutrophication of water bodies, deterioration of surface water environment, over-standard of groundwater nitrate content etc. The practices from the status and control of rivers and lakes in China showed that non-point source is the important source of water pollution; especially, agricultural non-point source pollution has become main reason of water environment deterioration and lakes (or reservoirs) eutrophication. “Three rivers and three lakes” controlled for a long term are not clean now, which are all related to non-point source pollution. In recent years, the eutrophication of lakes is severe, for instance, Taihu lake, Chaohu lake, Dianchi lake, Guanting reservoir, Donghu lake and so on have very poor water quality, lose basically water supply function and are difficult to be renewed. The eutrophication in Yuqiao reservoir of Tianjin city, Qiandao lake of Zhejiang province, Xiashan reservoir of Shandong province, Erhai lake of Yunnan province are all related to non-point source pollution. According to the investigation from non-point source pollution loading of Dianchi Lake in 1987, the results showed that 31.2 percent of nitrogen loading and 44.9 percent of phosphorus loading come from non-point source pollution. With the implementation of point source pollution controlling, the ratio of non-point source pollution loading is on the increasing tendency (KRDES, 1992). The statistical results from non-point source pollution loading of Zhutuo cross section in Yangtze River in 2004 showed that TN and TP produced by non-point source account for 65.6% and 95.7 % of total pollution loading.

In the recent 20 years, the pollution loading is increasing rapidly with the improvement of agricultural production and living standard, but the wetlands and alongshore vegetation that could block non-point source pollution is degrading rapidly. There are various reasons to cause water environment pollution. The eutrophication of most lakes in China is induced by nitrogen and phosphorus. The water and soil erosion, unreasonable application of agricultural fertilizer and pesticide etc. are the important reasons to cause the pollution of rivers and lakes and deterioration of the groundwater. With the development of society, the water consumption is continuously growing, the wastewater discharged into rivers, lakes and reservoirs is also constantly enhancing. Although the treatment rate of wastewater is continually improving, the yearly discharge of wastewater is still increasing on a large scale. The total discharge of the wastewater was 41.52 billion m^3 in 2000, 52.45 billion m^3 in 2005, of which 24.31 billion m^3 was released from industry, and 28.14 billion m^3 from municipal. Due to water shortage, the diluting capacity of water bodies is low; furthermore, the water environment tends to deterioration. In addition, the unreasonable development and utilization of water and soil resources, such as a large amount of agricultural consumption, are also one of the reasons of water environment deterioration. At present, the water pollution problems in China are developing from east to west, extending from tributaries to main rivers, spreading from cities to rural areas, penetrating from ground to underground, diffusing from regions to watersheds.

MAIN POLLUTION SOURCES AND FEATURES OF NON-POINT SOURCE

Increase of Fertilizer And Pesticide Consumption Year After Year

The cultivated land in China takes only up 7 percent of world′s cultivated land, but the fertilizer consumption accounts for about 25 percent. The fertilizer consumption in China is the largest in the world, and on the increasing tendency year after year. Since the beginning of 1980s, the application of fertilizer in China was vigorously encouraged so that total consumption of fertilizer increased from 12.694 million m^3 in 1980 to 41.464 million m^3 in 2000, with the increase of 2.3 times, the corresponding grain yield raised from 0.32 billion m^3 to 0.462 billion m^3 , increasing 44 percent. The grain yield in 1998 reaches the maximum of 0.512 billion m^3, subsequently, although the fertilization amount is still increasing, the grain yield is not synchronously growing (NBSC, 2005), seeing Figure 3. At the same time, the fertilizer use unit area in 2000 reaches 319kg/hm^2, among which the application of nitrogen (N), phosphorous (P) and potassium (K) fertilizers has various degrees of increase, the consumption of N, P and K fertilizers in 2000 reaches 21.616, 6.905 and 3.765 million m^3, respectively The unreasonable application of fertilizers consists in excessive consumption of N and P fertilizers, deficient consumption of K fertilizers, and unbalance application among the regions. The cultivated area lacking K in China accounts for 56 percent of total cultivated area. The 20%~30% of cultivated land has excessive nitrogen nutrient (SEPAC, 2001). Due to extensive fertilization and irrigation

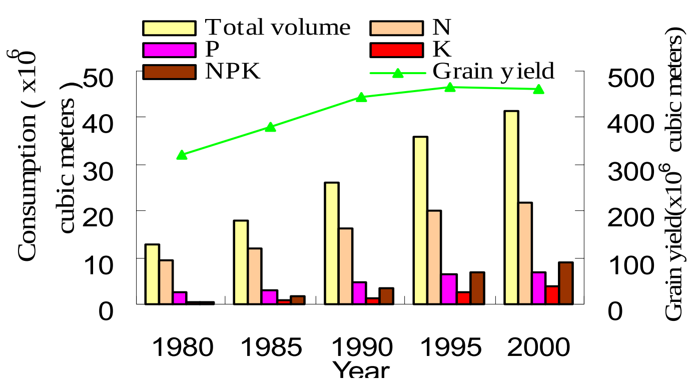


Figure 3. Fertilizer consumption from 1980 to 2000 in

technology, the application efficiency of fertilizers is on the low side, averagely only 30 to 40 percent, 60 to 70 percent of fertilizers comes into environment and pollutes water bodies and soil (Hu et al; 2005). A large amount of N and P nutrients contained in the farmland drainage and rainwater enter the rivers and lakes, and result in severe worsening of water quality.

The consumption of pesticides tends to increase in recent years, such as 0.733 million m^3 in 1990, 1.087 million m^3 in 1995, and 1.28 million m^3 in 2000 with about 14kg/hm^2 of dosage, but the application efficiency is less than 30 percent (Li et. al,2006). The pesticide variety has the characteristics of diversity, low quality, low efficiency, high toxicity， high residue content contained in farm products. Owing to excessive application of pesticides, the natural enemies of pests or other beneficial insects are decreasing rapidly so that vicious circle of supplemental pesticides application is caused. A large amount of pesticide loss comes into air, water bodies, soil and farm products; some pesticides that are difficult to be decomposed are remained in the soil and accumulated year after year. The natural environment is affected at different degrees and the poisoning events caused by pesticide occur sometimes.

Severe Water And Soil Erosion

China is a country with serious water and soil erosion. The area of water and soil erosion in China totals to 3.56 million square kilometers， taking up 37 percent of total area of the whole country. According to statistics, the eroded soil is about 5 billion m^3 every year which is equivalent to 1cm soil layer from the cultivated land of the whole country, among which the lost soil is about 2.4 billion m^3 in the Yangtze River Basin and 1.6 billion m^3 in the loess plateau of Yellow River Basin. The lost N, P and K are more than 40 million m^3 (Qian,2000). The water and soil loss results in the decrease of cultivated area, degradation of land, sediment silting in rivers, lakes and reservoirs. And a large amount of nutrient substance contained in water and soil becomes the pollution sources of water bodies. In the recent 30 years, although a lot of water and soil conservation works has been carried out, the water and soil erosion has the spreading trend at the larger region.

Increasingly Graveness of Agricultural Production And Domestic Rubbish Pollution

The cultivated land in China is 0.13 billion hectares; the yearly yield of crop straw is more than 0.6 billion m^3. A mass of straw is set on fire or discarded in two sides of rivers, lakes, canals or roads, which wastes not only the biology and energy sources, but also pollutes air and water bodies, and even affects the traffic (Hu, 2000).

With the development of rural economy and increase of farmer's living standard, the domestic rubbish and wastewater discharge are increasing year after year. In 2001, China discharged a total of 8.32 billion m^3 of domestic wastewater from rural areas, among which COD, TN and TP are 8.321, 0.582 and 0.1415 million m^3, respectively. Owing to low environmental consciousness in rural areas, dispersiveness and particularity in the agricultural production and living, and severe lag of basic establishments, the utilization efficiency of domestic rubbish is very low so that a majority of domestic wastewater and rubbish is dumped into water bodies without treatment and makes rural ecological environment worsening.

Rapid Development of Livestock And Poultry Breeding

With the development of agriculture and rural economy, the utilization of animal excretion has not been developed synchronously. Compared with quick-acting fertilizers, the ratio of animal excretion used as manure is constantly declining. In recent years, the livestock and poultry breeding is developing rapidly, especially, the intensive livestock and poultry breeding has become important pollutants of rural non-point source pollution. The contributing rate of livestock and poultry breeding in the agricultural production value has gone up from 14% in 1970 to 30% in 2000, but at the same time, a large amount of animal excretion is also produced. According to the investigation, the animal excretion in 1999 reaches 1.9 billion m^3, which is 2.4 times of the discharge amount of industrial solid wastes, and the excretion amount from extensive livestock and poultry breeding takes up 30 percent of industrial solid wastes. The COD discharge from animal excretion reaches 71.18 million m^3, and exceeds greatly the summation of industrial and domestic wastewater. The investigation showed also that the warning value of land loading from animal excretion already reaches 0.49, forming the obvious threat to ecological environment(Qian,2000).

The livestock and poultry breeding has brought serious influence for environment, and its main behaves are that animal excretion or organic wastewater with high concentration enters into rivers and lakes to make water quality worsening, the fetor gas pollutes the air and the high concentration wastewater irrigating the farmland affects the soil quality. The manner of livestock and poultry breeding in China is mainly dispersive breeding. In the distribution range or pollution discharge character, the dispersive breeding behaves still with non-point source pollution. The treatment level of animal pollutants has not obvious improvement so that total volumes of animal pollutants are rising steadily, constituting an important aspect of rural non-point source pollution.

CONTROLLING TECHNOLOGY AND APPLICATION STUDY OF NON-POINT SOURCE POLLUTION

Since the 1980s, China has realized gradually the harm of non-point source pollution. Some researches on urban runoff pollution and agricultural non-point source pollution etc. have been carried out. In the controlling of agricultural non-point source pollution, amending fertilizer characters and reducing fertilizer consumption etc. are used for lessening the losses of nitrogen and phosphorus. In the treatment of rural domestic wastewater, the dispersive treatment technologies are being studied, such as land treatment system, artificial wetland treatment system etc. In the treatment of rural domestic rubbish and solid wastes from agricultural production, the wastes are often treated by some technology in order to make them reused. In the treatment of surface runoff, multi-ponds system and pre-tank technology and so on are also being experimentally studied.

Controlling And Management of Non-Point Source Pollution

The controlling and management of non-point source pollution in China has not pertinent compulsive regulations at the nationwide scale. With the increasing graveness of non-point source pollution problems, more and more organizations and personnel devoted their efforts to this work. Some results have been obtained in the field of non-point source loading estimation, controlling measures, quantitative modeling and GIS application. These researches focus mainly on the following aspects.

（1）Technologies controlling farmland pollution：By the way of reducing the pollutant amount from the sources, non-point source pollution entering the rivers is controlled, including optimal fertilization technology, water and soil management measures in the farmland, multi-ponds systems or pre-tank technology, ecological canals (or ditches) blocking N and P. The study of pre-tank demonstration pilot in Dianchi watershed showed that the removal rate of silt, TN and TP is about 95%, 80%～90% and 75%～90%, respectively.

（2） Technologies controlling animal excretion pollution: Animal excretion reuse by compost, or used as biogas; straws returning; reducing the flushing water for animal houses, and treating respectively the solid and liquid wastes from barnyard; changing feed components to reduce the animal excretion and pollutant concentration in the excretion.

（3） The impacts of the wetlands, forest ecosystems, buffer zones etc. on controlling mechanism, effect and application of non-point source pollution have been experimentally studied in many places. The study showed that the wetlands have better treatment capacity and steady treatment effects for organic matter, N and P. The results from the wetland controlling in Dianchi Lake showed that the wetland area accounts for about 1%～2% of controlled area and the removal rate of pollutants from wetland is between 60% and 80%, with the maximum of over 90%～95%.

（4）Quantitative researches of non-point source pollution：Based on the analysis of water volume and water quality for water bodies, some experiential models of pollution loading estimation are established, or the pollution loading amount is estimated based to wastewater discharge coefficient of different land types. Some mechanism models are also established to model runoff, water and soil erosion and pollutant transport. Based on available models, such as SWAT, AGNPS etc., non-point source pollution for some watershed, lakes or regions is appraised.

Application Practice of Non-Point Source Pollution Research

Taihu-lake region is one of the most developed areas in China. There are abundant rainfall, many rivers and branches here. Due to intensive land uses, excessive and unreasonable fertilization, the N and P nutrients from farmland drainage have become main pollution sources of water body eutrophication. Thus, to reduce the concentration of N and P nutrients in the drainage will be one of important measures to control effectively the eutrophication of water bodies.

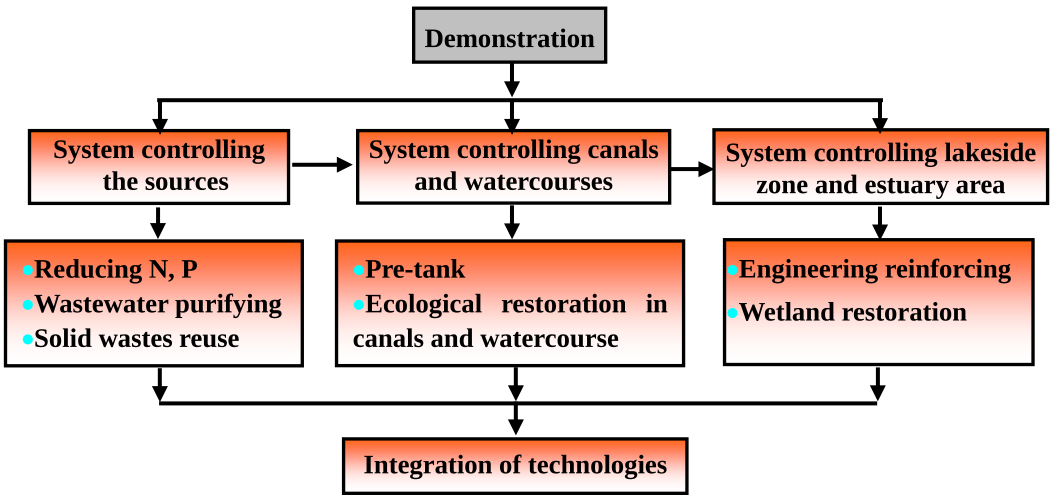


Figure 4. Controlling systems for non-point source pollution in rivers network of Taihu Lake

Based on a case study in rivers network in Taihu lake funded by national "tenth-five years" planning, a set of technologies controlling non-point source pollution are set up, including a system controlling the source pollution, a system controlling canals and watercourses pollution, and a ecological restoration system in the lakeside zone and estuary area, seeing Figure 4. The system from the sources includes the controlling technologies of fertilizers, pesticides etc., treatment technologies of domestic wastewater and solid wastes. TN and TP in the farmland drainage go down 40 percent by saving N, controlling P, reducing pesticide dosage, and artificial compulsive ecological blocking. The removal rate of domestic wastewater is over 70% for TN, over 90% for TP by using ecologic soil and vegetation planting etc. In the system of canals, ditches and watercourses, artificial compulsive pre-tank system using natural ponds is built, the residual N and P from surface runoff, domestic wastewater and solid wastes are treated by mechanical and physical function of runoff stagnating, silt sedimentation, hydrophyte adsorbing etc., the removal rate of TN, TP and silt is 70%, 80% and 90% respectively. At the same time, by aquatic plants and microbe function in the canals, ditches and rivers, N and P will be further reduced. Finally, the removal rate of outlet water is 60%~80% for BOD, 40%~50% for COD, 50% for TN, 70% for TP in the system of canals, ditches and watercourses. While the runoff from watercourse flows into lakeside zone and estuary area, the removal rate of pollutants (SS) and TP reaches 50% and 35% by physical, biological and ecological purification.

The project built a 24 square kilometer of demonstration plot. The removal rate of BOD, COD, TN and TP reaches all the required standards. The water quality of controlled cross section in the estuary flowing into lake, and ecological restoration area increases a grading than 2002. The rural ecological environment in the river network area is improved as a whole.

EXISTING PROBLEMS AND PROSPECTS OF NON-POINT SOURCE RESEARCH

Existing Problems

Although the research on non-point source pollution acquired the great development, it lags far behind the developing tendency of non-point source pollution. The available main problems are involved as follows.

（1）In the basic investigation of non-point source pollution, there are more partial works, and less comprehensive and systemic works at the nationwide range. The controlling measures and management are scattered and have not formed an integrated system. The results at small regions are difficult to be extended to larger area.

（2）The purification study by aquatic plants and microbe etc. is still in the experimental stages, and necessary to be popularized at the large scale.

（3）The model researches are inadequate. There are more experiential models and less applied models. Most models oversimplify the pollutant estimation, and lack the research of transformation mechanism of pollutants. The watershed models are short of data supporting with corresponding precision, influencing the further development of non-point source models.

（4）The establishment and implementation of management policies are very slow so that the studies of non-point source pollution are separated with management planning of national water quality. The popularization services of agricultural technologies are weakness and the public is short of the consciousness of environmental protection.

Research Prospects

The non-point source pollution in China is the most pressing problem to be solved. In order to control effectively non-point source pollution, the scientific investigation, controlling theory and technology researches should be reinforced, and management measures and legislation researches should be also enhanced.

（1） Emphasizing and strengthening the investigation：Developing the investigation of non-point source pollution at the nationwide range; Founding the investigation points at selected important regions and understanding the pollution sources, transport laws and pollution loading by long term observation in order to provide reliable information for technology study and policy establishment.

（2）Strengthening theoretical study and application practices of management policies:

Integrating overseas successful experiences into China's situation and establishing legislation system for compulsively carrying out non-point source controlling; studying the solutions by using economic measures, education and voluntary negotiation.

（3）Strengthening the technological research and popularization: Perfecting the evaluation system of agricultural environmental safety; Popularizing well-rounded fertilization technology and planting technology, and promoting the extending application and demonstration; strengthening the construction of the popularization system and implementing the comprehensive management of watershed.

（4）Strengthening the information dissemination of environmental protection: The indifferency for environmental protection is an important factor of non-point source pollution. It is the important to enhance the environmental protection and participant consciousness of public, especially the consciousness of farmers, and leading farmers to scientific farming, fertilization, crop-dusting and so on.

（5）Strengthening the application of new technology and methods: Integrating 3S technologies into non-point source pollution models and establishing the spatial database of non-point source; studying non-point source distributing models suitable for China's situation.

REFERENCES

Hu Daize. Utilization status and prospects of crop straw resources in China[J]. Resources development and market. 2000，16(1)：19-20

Hu Hongxiang, Tianqiu, Hong Youhua Ma. Agricultural Non-point Source Pollution and Its Tactics of Preventing and Curing[J]. Chinese agricultural science bulletin. 2005，21(4):315-347 (in Chinese)

Kunming Research Department of Environmental Sciences. Investigation Research of Eutrophication at Dianchi[M]. Yunnan science and technology press, 1992.2 (in Chinese)

Liu Hongxia, Jianguo Tao, Jianfang Wang, Baoping Han. Livestock and Poultry Pollution and Circular Economy[J]. Pollution Control Technology. 2003,16(3): 14-18 (in Chinese)

Li Zitian, Ruibin Hao, Fang Shen. Agricultural Sustainable Development against Ecological and Environmental Problems and its Countermeasures[J]. Agricultural Equipment Research. 2006 (1)：21-24 (in Chinese)

Qian Yi. Environmental protection and sustainable development[M]. Beijing: Higher education press,2000 (in Chinese)

National Bureau of Statistics of China. China Statistical Yearbook-2005[R]. China Statistics Press, 2005 (in Chinese)

State Environmental Protection Administration of China. 2000's report about the condition of China' environment. Environmental protection. 2001,(7):3-9.(in Chinese)

State Environmental Protection Administration of China. 2005's report about the condition of China' environment. http://www.zhb.gov.cn/plan/zkgb/05hjgb (in Chinese)

OAKDALE IRRIGATION DISTRICT WATER RESOURCES PLAN — A CALIFORNIA WATER MANAGEMENT CASE STUDY

Steven R. Knell, P.E.[1]
Gregory W. Eldridge, P.E.[2]

ABSTRACT

In response to a range of internal and external drivers and the need to protect the district's pre-1914 water rights, Oakdale Irrigation District (OID) developed a long-term Water Resources Plan (WRP). The 100-year-old irrigation district provides irrigation and domestic water service to over 55,000 acres in California's San Joaquin Valley.

The study effort created a strategic roadmap for the implementation of a $170 million capital program focused on protecting OID's water rights while meeting the changing needs of its constituency and serving the region. The second phase included programmatic environmental documentation, which is being followed by design and construction of facility improvements.

This multi-disciplined effort included detailed land use modeling, water balance modeling, on-farm surveys, a comprehensive infrastructure assessment, and the development of a phased infrastructure plan to rehabilitate and modernize an out-of-date system. The approach also integrated water right evaluations, groundwater studies, development and evaluation of program alternatives, financial analyses, environmental compliance, and public outreach.

Key benefits resulting from WRP implementation include protecting the district's water rights, increasing reliability during droughts, and modernizing a century-old system to meet the needs of its current and future customer base. Implementation includes a balanced effort of water transfers and expansion of service into OID's sphere of influence while keeping water rates affordable. OID's infrastructure will be rebuilt, modernized, and expanded, and customer service and water use efficiency will be enhanced.

INTRODUCTION AND BACKGROUND

Purpose and Scope of the Water Resources Plan

Oakdale Irrigation District (OID) is a nonprofit, local public agency that operates as a political entity of the State under the California Water Code. This is the district's mission:

To protect and develop Oakdale Irrigation District water resources for the maximum benefit of the Oakdale Irrigation District community by providing excellent irrigation and domestic water service.

---

[1] General Manager, Oakdale Irrigation District, 1205 East F Street, Oakdale, CA, 95361; srknell@oakdaleirrigation.com

[2] Vice President, CH2M HILL, 2485 Natomas Park Drive, Suite 600, Sacramento, CA, 95833; geldridg@ch2m.com

The complexity of water issues, both locally and at the state level, necessitated a rethinking of OID's current practices and priorities in order to guarantee full protection of the district's and region's water supplies into the future. The District's Board of Directors and management commissioned CH2M HILL to explore the issues facing OID and develop a comprehensive plan to respond to these issues. These were the principal objectives of the Water Resources Plan (WRP).

In the development of the WRP, the OID Board of Directors developed the following five goals that they agreed to be key to developing water management strategies and alternatives:

- Provide long-term protection to OID's water rights
- Address federal, state, and local challenges
- Rebuild and modernize an out-of-date system to meet changing customer needs
- Involve the public in the planning process
- Develop affordable ways to finance improvements

The WRP evaluates the district's water resources, delivery system, and operations, and examines land use trends to determine how future changes in these areas will impact water supply and demand during the next two decades. The plan also provides specific, prioritized recommendations for OID facility improvements that will comply with the California Environmental Quality Act (CEQA) and accommodate available financial resources.

General Background

OID is located in the northeast portion of the San Joaquin Valley, about 30 miles southeast of Stockton and 12 miles northeast of Modesto, as shown in Figure 1. The OID service area consists of 72,500 acres between the Sierra Nevada and the Central Valley along the San Joaquin–Stanislaus county line, surrounding the city of Oakdale and bordering the cities of Riverbank and Modesto. The district's sphere of influence (SOI)—land that the district is permitted by law to annex, but to which it has not yet provided service—extends 86,290 acres farther to the north and east into Calaveras County. The Stanislaus River flows from the east through the center of the district service area and SOI.

Situated near the base of the Sierra Nevada foothills, OID's topography varies from gently rolling hills to the east and south of Oakdale to nearly flat around Riverbank. Approximately 75 percent of the land within the OID service area consists of irrigated agriculture. Native vegetation and rangeland dominates the land immediately outside the OID service area to the north, south, and east.

OID experiences mild, moderately wet winters and warm, dry summers typical of the Central Valley. Average temperatures range from the mid-forties in winter to the mid-nineties in summer. Precipitation averages about 12 inches annually, over 85 percent of which occurs between November and March. Average evapotranspiration (ET) is approximately 46 inches seasonally (April through October). Climate conditions are generally uniform throughout the district.

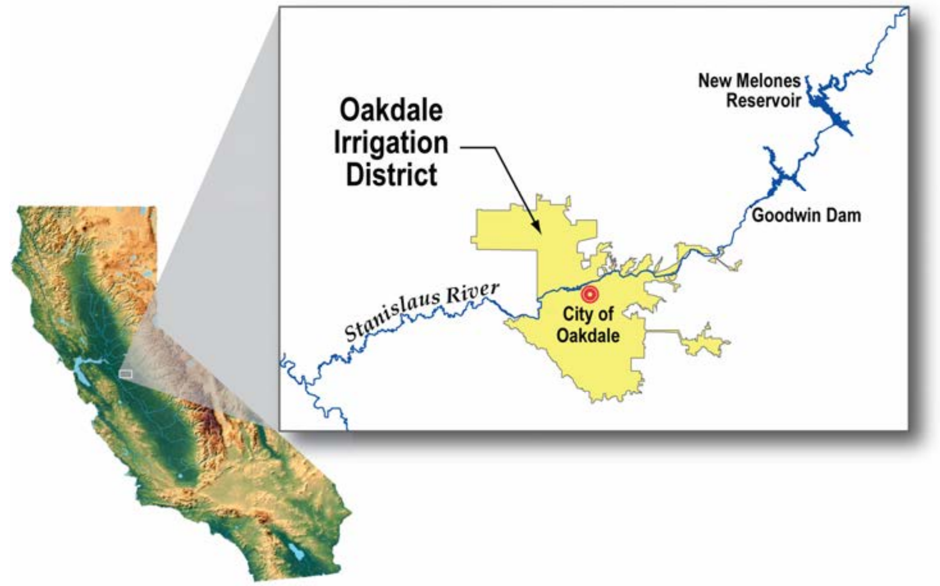


Figure 1. Location of Oakdale Irrigation District

History of OID

In 1909 OID was organized under the California Irrigation District Act by a majority of landowners within the district in order to legally acquire and construct irrigation facilities and distribute irrigation water from the Stanislaus River. In 1910 OID and the neighboring South San Joaquin Irrigation District (SSJID) purchased Stanislaus River water rights and some existing conveyance facilities from previous water companies. The districts continued to expand their facilities and infrastructure over the next several decades.

Since their creation, OID and SSJID have constructed dams and reservoirs to regulate surface water storage and deliveries. Most dams were constructed in the 1910s and 1920s, including Goodwin Dam (1913), Rodden Dam (1915), and Melones Dam (1926), which provided 112,500 acre-feet (ac-ft) of shared capacity. To provide supplemental water storage for OID and the SSJID, the Tri-Dam Project was created in the 1940s. Sites were approved in 1948 for Donnells Dam and Beardsley Dam on the Middle Fork Stanislaus River, and Tulloch Dam above Goodwin. The two districts entered a joint agreement to carry out the proposed project and now jointly own and operate the three storage reservoirs for a combined storage capacity of 230,400 ac-ft.

In the early 1970s Reclamation replaced the Melones Dam with the larger New Melones Dam and Reservoir. The districts have an operations agreement with Reclamation to utilize the federally owned New Melones Reservoir.

Significant capital investment has led to a stable, plentiful water supply for the district. Over the last 50 years, the district has focused its financial resources on paying off these capital investments; as a result, few new facilities have been constructed during that time, despite changing demographics and land use in the surrounding area that have influenced demand for OID’s services.

Budget and Sources of Revenue

The OID Board of Directors strives to distribute water equitably to the water users at cost. The budget is set annually by the Board.

Revenues District revenues totaled $8.8 million in 2004 and are budgeted to reach approximately $10 million in 2005. The sources of these revenues are shown in Figure 2. Revenues generated from normal district operations total between $3.6 and $3.9 million, while non-operating and joint-venture revenues contribute the remaining funds. On average, the Tri-Dam Power Project contributes approximately $4.4 million to OID's annual revenue, depending on water year type.

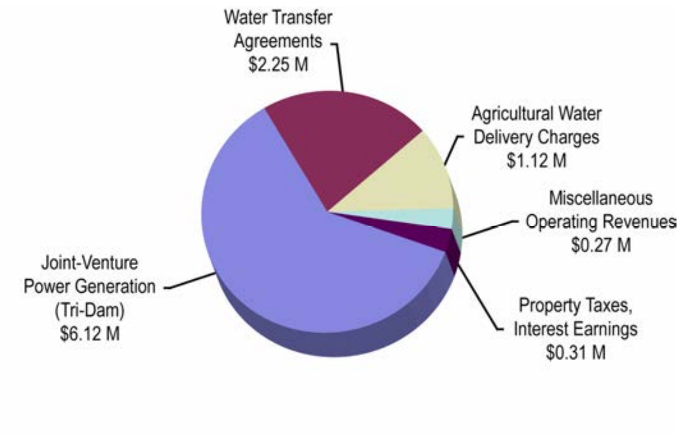


Figure 2. 2005 OID Budget Revenues

Power generation from both the Tri-Dam Power Project and the Tri-Dam Power Authority accounts for over 60 percent of the district's total revenue. Water transfer agreements and agricultural water delivery charges also contribute approximately one-third of net revenue. Domestic water charges and taxes provide only a slight contribution to total revenue.

Expenditures Budgeted expenditures for 2005 total approximately $11.9 million. Expenditures consist mainly of operations, maintenance, and administrative activities, as shown in Figure 3. About one-fifth of all expenditures consist of capital purchases and projects. Capital replacement projects make up 82 percent of capital expenditures, while capital improvements and purchases make up 10 and 8 percent, respectively.

In the past the district focused on meeting maintenance needs as they arose, because the financial means were not available for significant modernization of facilities. The district's financial position has recently improved as a result of the payment completion on a large bond issue. The district also anticipates increases in revenues from its power generation facilities following relicensing. As a result, the district plans to invest a much greater percentage of its revenues in facilities and organizational improvements.

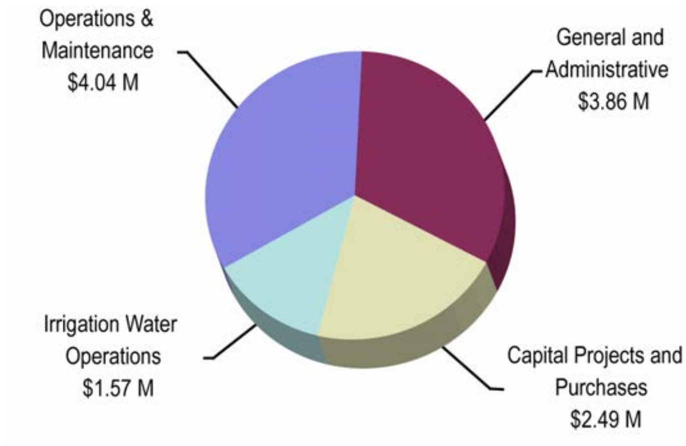


Figure 3. 2005 OID Budgeted Expenditures

The District Today

Currently, the district maintains over 330 miles of laterals, pipelines, and tunnels, 29 production wells, and 43 reclamation pumps to serve local customers. In general, the district's facilities, system operations, political organization, and administration have not changed significantly over the last several decades. Nearly all water supply canals were constructed more than 50 years ago. In recent years, however, the district's customers, land use, and financial resources have developed in a direction that may influence the way OID provides services and conducts business.

OAKDALE IRRIGATION DISTRICT FACTS

Year OID was organized: 1909

Cost to OID and SSJID for existing irrigation system and water rights in 1910: $650,000

Total district acreage: 72,500

Total irrigated acres: 55,600

Annual diversion right: 300,000 acre feet

Diversion point: Goodwin Dam

Maximum diversion rate from Goodwin Dam: 910 cfs

Total distance of water delivery system: 330 miles of canals (open, lined, and buried pipelines)

Number of agricultural wells: 24

Number of agricultural and domestic water accounts: 3,500

Percent of OID agricultural customers who farm parcels of 10 acres or less: 60 percent, constituting 12 percent of OID land

Percent of OID agricultural customers who farm parcels of 40 acres or more: 4 percent, constituting 60 percent of OID land

The combined storage capacity for Tulloch, Beardsley, and Donnells Reservoirs: 230,400 ac-ft

Combined power generation by the Tri-Dam Power Project: 81,000 kilowatts

Analyses and Findings

Analyses conducted for the WRP included detailed land use modeling, water balance modeling, on-farm surveys, a comprehensive infrastructure assessment, and the development of a phased infrastructure plan to rehabilitate and modernize an out-of-date system. The integrated approach also included water right evaluations, groundwater studies, development and evaluation of program alternatives, financial analyses, environmental compliance, and public outreach. The following discussion summarizes some of the key analyses conducted in the study.

Land Use

OID currently serves 2,800 agricultural customers on approximately 55,600 acres of serviceable land. The district also provides water to 700 domestic accounts primarily east of the City of Oakdale.

Agriculture dominates the lands in and surrounding OID, as shown in Figure 4. Within the district service area, pasture makes up approximately half of the total land use, or about 32,000 acres. The other half of the district consists of orchards, corn and oat crops, and municipal land in relatively even proportions. Only a small percentage of the land in the district's service area consists of native vegetation.

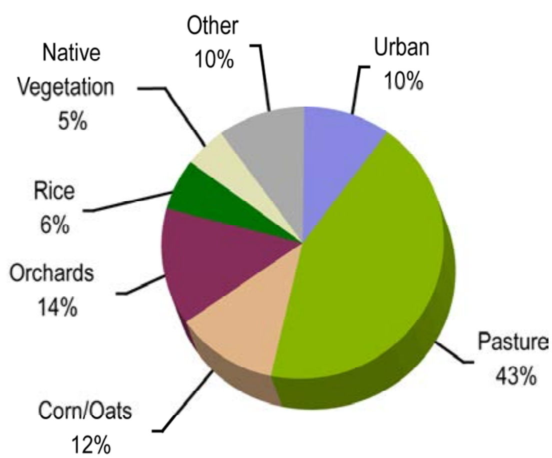


Figure 4. Land Use Distribution in OID

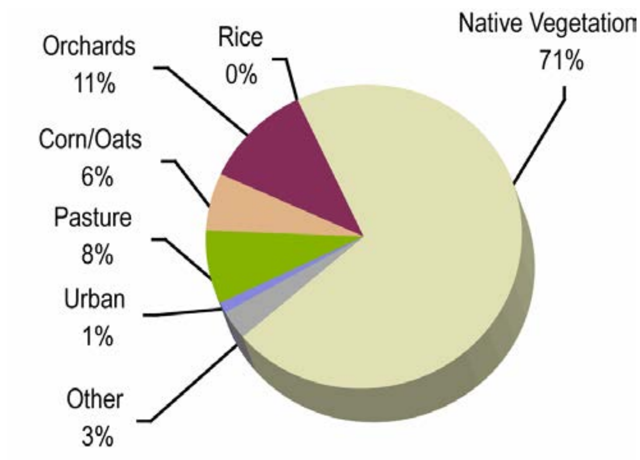


Figure 5. Land Use Distribution within OID Sphere of Influence

Outside the OID service area but inside the district's SOI, native vegetation dominates three-quarters of the land, or approximately 47,000 acres, as shown in Figure 5. Orchards and pasture crops make up 11 percent and 9 percent, respectively. Corn and oats make up 6 percent. Rice and urban/industrial areas make up 1 percent or less of the district SOI outside the service area.

Land use within the OID service area has shifted in recent years, and these trends point to continued change in the future. Some agricultural land around the cities is urbanizing. The City of Oakdale is experiencing steady population growth. It is forecasted that over the next 20 years, 6,000 acres of agriculture in OID will be replaced by municipal land, resulting in fewer irrigated acres and a lower demand for OID water.

Many OID customers are also changing the types of crops they are growing. Across the region, higher-value tree crops are replacing pasture. Orchards use less water and require a more intensive, responsive level of irrigation service than is currently provided by the district. Land ownership is also changing as large parcels are subdivided, leading to increased ranchette-type development in some areas. All these factors may necessitate changes to the level of services the district can currently provide.

Of particular note is that orchard acreage outside OID's existing service boundaries has more than doubled in the past decade. This is the result of accelerated market conditions for nut crops. The irrigation water source for orchards outside OID is almost exclusively groundwater. The majority of orchard development has occurred immediately adjacent to OID's eastern boundary. This development offers significant opportunity for expansion of service by OID.

Forecasted Trends As shown in Figures 6 and 7, forecasted land use inside and adjacent to the current OID service area is expected to continue changing substantially.

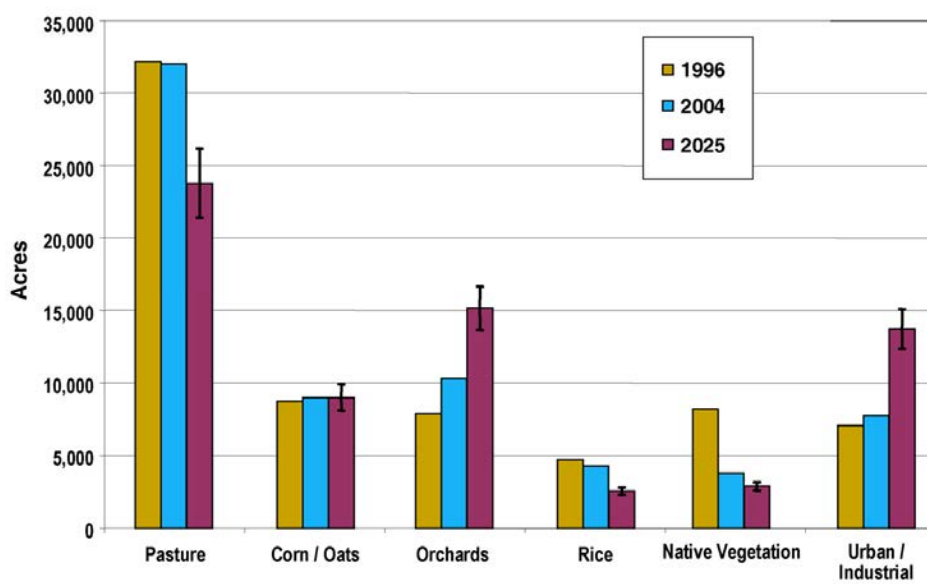


Figure 6. Historical and Forecasted Trends Inside OID Service Area

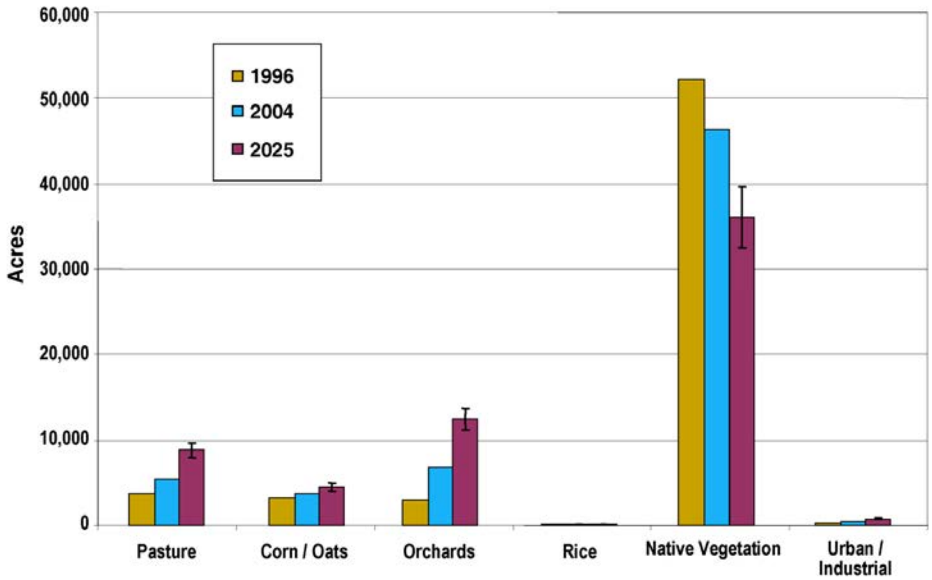


Figure 7. Historical and Forecasted Trends Outside OID Service Area

While pasture is generally projected to decrease within OID, orchards are expected to increase nearly 50 percent to approximately 15,000 acres in 2025. Nearly all these orchards are expected to implement fairly efficient irrigation systems (such as microsprinklers), resulting in significant water savings. It is expected that most orchards (average applied water approximately 3 ac-ft per acre) will be planted on ground that was previously pasture (average applied water approximately 6 ac-ft per acre). This will result in the applied water demand being essentially cut in half. Also, the efficiency of the irrigation systems will result in other water savings, including reduced—and in many cases eliminated—tailwater production.

The forecasted 2015 City of Oakdale population is 29,000. Actual holding capacity of the 2015 boundary area, if completely built out, would be about 39,000. New residential growth through 2015 is forecasted to occur in all directions around the city, and will likely fill in four primary areas within the 2015 growth boundary. Accounting for additional urbanization between 2015 and 2025, 10 percent of total current OID lands, most of which is currently irrigated agriculture, will likely be lost to urbanization by 2025.

Land Use Conclusions Historical land use and forecasted changes will significantly influence the future of OID and service to its customers. Forecasted land use is a fundamental element of the WRP and has significant influence over the suggested recommendations for the future.

Infrastructure Assessment

As part of the WRP, a detailed infrastructure assessment was conducted and concluded that major vulnerabilities exist with the OID primary water delivery system and that a large proportion of the system has significantly deteriorated. Additionally, changing customer needs and service conditions require that OID modernize its system to provide more responsive and reliable service. Assessments were conducted for these areas of the OID water delivery system:

- Joint Main Canal, North Main Canal, and South Main Canal
- Regulating reservoirs
- Primary distribution system
- Groundwater wells
- Drainwater and reclamation facilities
- Supervisory Control and Data Acquisition System (SCADA)
- OID's standards for providing irrigation service to its customers

Water Balance Modeling

The WRP documented water supplies available to OID, described efforts to assess the current OID infrastructure system and level of service, classified current land uses and forecast future uses within and surrounding the district, and summarized current on-farm practices. This information was integrated into the plan to develop and project the current and future use of water within the district. To facilitate this analysis, a systemwide operational water balance model (WBM) was developed. The WBM provides a flexible analytic tool for simulating a range of long-term operating scenarios and overall WRP alternatives.

The WBM is designed for systemwide analysis of water supply operations and accounts for the primary water balance components of the OID service area. The OID supply, conveyance, and drainage systems are represented via a "flow-path" schematic. Consistent with the infrastructure assessment and the land use analysis, the basic unit of analysis is the lateral service area (LSA), which is the geographic area supplied by a given supply lateral. The model uses a "demand-driven" water balance simulation, starting with the determination of on-farm water supply requirements (farm turnout delivery) for each LSA. The on-farm demand is determined by climate parameters, crop type, acreage, irrigation method, and average slope and soils properties. Supply sources such as surface water (Stanislaus River diversions), groundwater, and drainwater reclamation are used in a prioritized manner to meet the on-farm demands. Conveyance system losses, such as seepage and operational spills, are estimated for each LSA and included in the overall water balance accounting. Drainage basin inflows, reclamation pumping, and net outflows are tracked. The model runs on a weekly time-step for approximately a 30-week irrigation season.

The OID WBM runs on a general simulation commercial software platform called EXTEND. The model platform is used to develop "objects," or elements of the system making up the water balance. Examples of the model objects are the LSAs, groundwater wells, main canals, and drainage basins. Each component has user inputs to define system parameters, and linkages to other components that make up the overall flow-path of water through the OID service area. The model provides a graphical user interface based on a schematic flow path representation of the OID water system components.

The primary water balance unit of analysis is the LSA. Each LSA represents the portion of the OID service area supplied by a specific distribution lateral. Water supply into the LSA is provided by a combination of surface water, groundwater from wells, and reclamation pumps (drainwater). Water leaves the LSA through ET, deep percolation, tailwater spills to drains, and operational spills to drains. The drainage basin is the object in the WBM for tracking the supply, reuse, and outflow of drainwater. Each LSA overlaps one or more drainage basins, into which its tailwater and operational spills flow.

A baseline operations water balance was created to simulate the primary water components of OID's overall system under existing land use and varying hydrologic and climatic conditions. The baseline model was developed using 2004 land use information (which represents the most recent land use survey data available), irrigation efficiencies developed from an on-farm survey at OID, available outflow data from OID's boundary outflow program, and average- and drought-period climatic (ET and precipitation) records. Land use was developed using geographic information system coverage for OID's assessed parcels combined with California Department of Water Resources land use survey data. By starting with a baseline model that reasonably represents existing conditions, the model can then be used to evaluate the net impacts of key factors influencing OID's long-term water demand and supply, such as crop shifting and changes in farm efficiency levels, annexation of new service areas, varying levels of drainwater reclamation, groundwater pumping, and distribution system improvements.

The WBM was used to evaluate key water balance components for the OID system based on projected 2025 land use and assuming various climatic and hydrologic conditions. These analyses supported the evaluation of programmatic alternatives for system modernization, service area expansion, and water transfers.

Alternative Development and Evaluation

The WRP evaluated the district's water resources, delivery system, and operations. It surveyed on-farm water use and practices. The needs and perceptions of OID customers, OID Board of Directors, OID staff, local and regional elected officials, and neighboring jurisdictions were surveyed and assessed. In conjunction with this comprehensive assessment, the WRP examined land use trends to project how future land uses will impact water supply and demand over the next two decades. Lastly, the water balance efforts provided insight on projected water use in and surrounding the district.

Under all likely scenarios for future land uses and demand for water within OID, the district's water supplies are more than sufficient to accommodate future in-district needs (provided that the WRP's suggested infrastructure repair and modernization and service recommendations are implemented). To address the expected changes in future OID customers' needs and to reasonably and beneficially use the district's water supplies, several alternatives were developed and evaluated.

Summary Description of Programmatic Alternatives Four distinct programmatic alternatives were developed based on extensive interaction with OID staff, the Board of Directors, and the public. These alternatives encompass a range of reasonable options available to the district in response to the land use, regulatory, resources, and customer-driven issues presented in the WRP. The term *programmatic* is used to emphasize that the alternatives evaluated in the WRP are broad-based and strategic, and represent policy-level options for OID's consideration. Highlights of the four programmatic alternatives are provided in the following sidebars.

ALTERNATIVE 1: CONTINUE PRESENT PRACTICES

Over recent years, OID has initiated several important efforts to improve management, operations, facility replacement, and long-term planning. OID has been engaged in several regional efforts related to water quality and groundwater management, has been conducting a moderate level of capital improvements to address the highest risks to the water delivery system, and has entered into three water transfer agreements to put its supplies to beneficial use and create additional revenue to fund improvements.

Alternative 1 generally consists of the following:

- Maintain existing level of service to OID customers.
- Implement an infrastructure plan that addresses high-priority improvements and major service liabilities but does not include any system enhancements to improve service or better manage system surface water outflow.
- Do not expand service to growers within the district SOI (no annexation or out-of-district water sales).
- Continues current level of water transfers.
- Participate in regional activities such as cooperative programs for groundwater management and water quality.
- Take only minimal action to improve OID system efficiency or customer on-farm water use efficiency.

ALTERNATIVE 2: MAXIMIZE SERVICE IMPROVEMENTS WITHIN DISTRICT BOUNDARIES

This programmatic alternative is similar to Alternative 1, but has the following significant differences:

- Improve level of service to customers (consists of operational, policy, management, and infrastructure improvements).
- Provide improved drought protection.
- Construct facilities to better manage OID surface water outflow.
- Establish new and/or revised water transfer agreements.

ALTERNATIVE 3: MAXIMIZE SERVICE IMPROVEMENTS WITHIN DISTRICT BOUNDARIES AND MODERATE EXPANSION OF SERVICE WITHIN OID'S SOI

Similar to Alternative 2, this variation allows for the moderate expansion of service into the district's SOI. This is the most balanced of all alternatives because it provides for service expansion while allowing water transfers as necessary to fund required improvements.

ALTERNATIVE 4: MAXIMIZE SERVICE WITHIN OID'S SOI

This alternative would maximize the use of available water for expanding service to growers within the district's SOI. Under this alternative, no water is available for transfer because all district water supplies are used to facilitate an expanded customer base.

<u>Evaluation Process</u> The WRP programmatic alternatives were developed and comprehensively evaluated using analytic and qualitative methods. From this analysis emerged the Best Apparent Alternative: the package of recommended facilities and actions for the district to advance as the basis for programmatic environmental documentation.

Elements Common to Multiple Alternatives With the exception of Alternative 1, all alternatives contain several common components and elements. For example, each alternative is predicated on the philosophy that OID must first provide dependable irrigation and domestic service to users within its service area before it considers either expanding service outside district boundaries or transferring water to other agencies. Other common features are the following:

- Revised service standard
- WRP recommendations implemented within district boundaries
- Uniform projections for land use
- Conservative projections for on-farm water use efficiency
- Improved water supply reliability

Evaluation Methodology Applying these common assumptions uniformly, a detailed methodology was employed to determine key water balance components for projected 2025 conditions for each programmatic alternative.

Next, decisions regarding the provision of service to customers outside OID but inside the SOI (annexation) and water transfers were made for each alternative. Lastly, a Financial Model was used to analyze various strategies for viably supporting each alternative.

The four alternatives, combined with the viable financial strategies for implementation, results in a set of 13 distinct options, all of which are financially and technically feasible. Following the evaluation, a matrix summarizing each alternative was then compared to the WRP goals. From this comparison emerged the Best Apparent Alternative. The results of the water balance analysis for each programmatic alternative are summarized in Table 1.

Table 1. Water Balance/Reliability Analysis: Summary of 2025 Transfer and/or Annexation Opportunities by Programmatic Alternative

Alternative	Description	Key Components
1	Continue Present Practices	Present practices consist of a minimum transfer obligation of 30,000 ac-ft up to a maximum of 41,000 ac-ft.
2	Maximize Service Improvements within District Boundaries	2025 firm transfer of 50,000 ac-ft Additional variable transfer of 17,000 ac-ft
3	Maximize Service Improvements within District Boundaries and Moderate Expansion of Service within OID's SOI	2025 firm transfer of 50,000 ac-ft 4,250 acres of expanded service in SOI to utilize 17,000 ac-ft
4	Maximize Expansion of Service within OID's SOI	16,750 acres of expanded service in SOI to utilize 67,000 ac-ft of available supplies

In multiple programmatic alternatives, an initial and final level of firm and variable water transfers are identified. A firm water transfer is defined as the quantity of water provided in every year, including droughts. Variable transfers are reduced during dry years as Stanislaus

River supplies to OID are curtailed. OID currently transfers water to a neighboring special district and to the federal Bureau of Reclamation. These existing transfers total 41,000 ac-ft. Of that volume, 30,000 ac-ft are firm and 11,000 ac-ft are variable. Over the course of WRP implementation, the quantities of firm and variable supplies available for transfer were forecast to increase to 50,000 ac-ft and 17,000 ac-ft, respectively. In Alternative 2, these supplies are assumed to be transferred. Alternative 4 assumes that these supplies support expansion of service into the SOI. Alternative 3 assumes that the firm quantity is transferred, and the variable quantity supports expansion of service into the SOI.

Evaluation Results The detailed Financial Model analyzed various strategies for viably supporting each programmatic alternative. This analysis, in conjunction with significant public and Board interaction, led to the selection of Alternative 3 as the Best Apparent Alternative. This alternative maximized improvements in the district, provided for moderate expansion into the SOI, most strongly supported all the WRP's goals, and kept water rates at a favorable level. Following Board endorsement, Alternative 3 was termed the Proposed Program.

THE PROPOSED PROGRAM

The Proposed Program included numerous specific components, including OID policy, organization, and facility improvements. To comply with the California Environmental Quality Act (CEQA), OID prepared a Programmatic Environmental Impact Report (PEIR) to address the potential environmental impacts resulting from implementation of the Proposed Program. The PEIR provided a broad, programmatic analysis of the potential physical and biological consequences of implementing the Proposed Program. The PEIR also identified mitigation where determined necessary to reduce the level of impact from actions associated with the Proposed Program. The Proposed Program components consist of the following:

- Flow control and measurement projects
- Canal Reshaping and Rehabilitation Program
- Groundwater Well Program
- Main Canals and Tunnels Improvements Program
- Pipeline Replacement Program
- Regulating Reservoir and Woodward Reservoir Intertie
- Turnout Replacement Program
- Drainwater Reclamation Program
- Surface water outflow management projects
- Water transfers
- Expansion into the SOI

CONCLUSION

The WRP was a comprehensive study of the district and surrounding region. The plan identified critical areas for improvements and practical funding options. During development of the WRP, several data sources were reviewed, and significant analysis was completed. Key components of the WRP development included public outreach and involvement, a water resources inventory of current operations, an infrastructure assessment of existing infrastructure, an assessment of the current level of service, an assessment of on-farm irrigation systems, and an evaluation of land use trends and land use forecasting. The information obtained from these studies was used to develop and project current and future water use within the district. To facilitate this analysis, a systemwide operational water balance model was developed to simulate the primary water components of OID's overall system. Information derived from the WBM was used to develop alternatives to address changes in land use, regulatory changes, available resources, and customer-driven issues and concerns. The outcome from the alternative evaluation process is the Proposed Program, which provides the following expected benefits:

- Protects OID's water rights
- Enhances customer service
- Rebuilds, modernizes, and expands OID's system infrastructure
- Protects the future water supply needs of local urban areas
- Keeps water rates affordable through a balanced effort of water transfers and expansion into OID's SOI
- Enhances local water supplies by 30,000 ac-ft
- Provides 17,000 ac-ft of supplies to new customers in the SOI
- Allows 50,000 ac-ft of water transfer
- Substantially increases water supply reliability and meets OID service needs in worst-case drought

USE OF INFORMATION TECHNOLOGY TO SUPPORT INTEGRATED WATER RESOURCES MANAGEMENT IMPLEMENTATION

Eng. Hisham Shehab[1]
Eng. Moamen El-Sharkawy[2]
Dr. Tom Sheng[3]

ABSTRACT

While progress with Integrated Water Resources Management (IWRM) is fundamental to sustainable development, a prerequisite for furthering this process is an effective computerized system that serves the data and information needs of all stakeholders, and promotes equity through good governance. Developing an IWRM information system is a challenge in developing countries with limited resources. In most developing countries, water information systems at local administrative levels are generally absent or severely degraded, and management decisions are mostly based on unreliable data and information. A lack of data and obsolete data capture and/or information management systems are common issues, resulting in inadequate data/information to support IWRM implementation. An innovative, inclusive approach is required that will unleash the full benefit of a number of powerful technologies to capture, manage, and disseminate water related data and information in a cost effective and sustainable manner.

The Egyptian Ministry of Water Resources and Irrigation (MWRI) has a long-term goal of reorganizing internal functions and operations through a process of local governance consolidation and ministry-wide decentralization, including de-evolution of authority to the local government level. With that, the MWRI has adopted a policy to integrate all water management functions at the district level to support the decentralized management process.

The USAID/Egypt-funded Livelihood and Income from the Environment (LIFE) Integrated Water Resources Management (IWRM) Project was designed to focus on implementing policy reform measures on a large scale, covering 27 irrigation districts over 1.2 million acres of Egyptian cultivated land. Implementation of the project began in October 2004 with three main objectives: (1) Consolidate MWRI district offices (i.e., irrigation and drainage) (2) Promote stakeholders' participation through the formation of Branch Canal Water Users' Associations (BCWUA), and (3) Support equitable allocation of water resources at the district level.

Under the equitable allocation of water resources objective, a series of activities were carried out to support the development of district water information systems. The effort focused on providing technical assistance on the design, construction, and implementation of information

[1] Senior Assistant Director of Works, Integrated Water Management Unit, Ministry of Water Resources and Irrigation, Cairo, Egypt, Hshehab@iwrmeg.org
[2] Senior Assistant Director of Works, Integrated Water Management Unit, Ministry of Water Resources and Irrigation, Cairo, Egypt, Msharkawy@iwrmeg.org
[3] Ph.D. Senior Water Resources Information Specialist ,Computer Assisted Development, Inc., USA, tsheng@cadi-usa.com

systems in support of water management decision making at the 27 irrigation districts. The information systems component of the project consists of two major technologies: database management and digital mapping systems. While the database management and mapping systems evolved independently, both are integrating, analytical, and strategic technologies that are complementary to each other. The convergence of both technologies offers extraordinary opportunities for producing information management tools that connect disparate, but indispensable, threads of spatial and non-spatial data across different information systems and management units. These tools create broader knowledge and understanding for decision makers at the district, directorate, and central levels.

This paper will discuss the development of the information systems that comprise the seven database management systems (six tabular and one geospatial) to provide timely information in support of decentralized decision-making for improving water management at the district level. These information systems have now been implemented at the 27 (Integrated Water Management Districts) IWMDs under the project with great success. It is anticipated that the information systems will be introduced and implemented by the MWRI at other districts in the near future.

INTRODUCTION

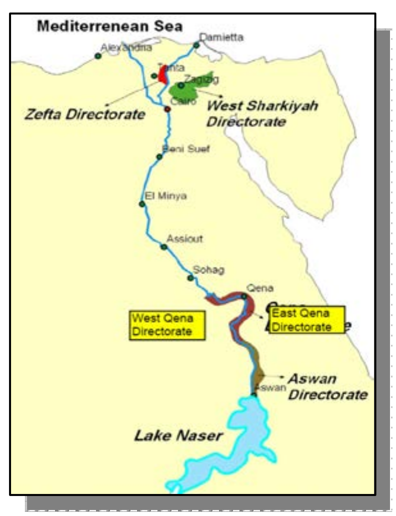
Under present operational and administrative conditions in the MWRI, the irrigation management services are carried out through line department directives and functions emanating from the central ministry to lower line offices at the inspectorate and district levels. The objectives of a policy reform were to move toward the goal of reorganization of the MWRI internal functions and operations, including devolution of authority to the local level, thereby decentralizing water management and eliminating district-level inefficiencies and redundancies.

An operational IWMD is expected to achieve the following targets:

- Improved water use efficiency
- Maintained irrigation and drainage system, and
- Improved service delivered to water users.

The definition an IWMD is:

The Integrated Water Management District is an entity that has sufficient manpower, material, and fiscal resources to operate and maintain all water resources under its jurisdiction [synthesis of several definitions; see APRP Report 49]. *All of the divisions support the water distribution process to ensure that water is delivered equitably, resulting in the various district water entities currently being merged to constitute a single entity referred to as an IWMD.*



The USAID/Egypt-funded Livelihood and Income from the Environment (LIFE) Integrated Water Resources Management (IWRM) Project was designed to focus on implementing policy reform measures on a large scale, covering 27 irrigation districts over 1.2 million acres of Egyptian cultivated land. Implementation of the project began in October 2004 with three main objectives: (1) Consolidate MWRI district offices (i.e., irrigation and drainage) (2) Promote stakeholders' participation through the formation of Branch Canal Water Users' Associations (BCWUA), and (3) Support equitable allocation of water resources at the district level.

PROBLEM DEFINITION

In order make to that, district managers require timely information and data to provide a greater understanding of their irrigation systems and system performance. The knowledge required to support improved water management at the district level is inherently spatial and analytical in nature. With that, the information systems development activities under the IWRM project were specifically designed to provide the IWMDs with the capability of managing all of the data/information needed to support decentralized and integrated water management decisions in the IWMDs.

Non-IWMDs currently collect data for higher levels to make management decisions for them. That is, non-IWMDs do not prepare their own water requirements and rotations. Instead, they are prescribed by directorates about three times a year. Basic information on physical system components, water resources quantity/quality, and water demands is outdated.

Spatial relations and representation of water resource data have not been a requirement in non-IWMDs because decision making was mainly taking place at the directorate level. The non-IWMDs and directorates both depended on the paper sketches or schematics for their physical system components. These sketches are based on grossly outdated 1950 paper maps of scales 1:25,000 and/or 1:50,000 printed by the Egyptian Survey Authority (ESA). The ESA is currently updating the maps for the entire country but the printed version is not yet available and a digital version is cost prohibited.

INFORMATION SYSTEMS DEVELOPMENT ACTIVITIES

Under the project, the information system component consists of two major information technologies: database management and digital mapping systems. The database management system consists of PCs, Microsoft Office, and six database applications. The digital mapping system consists of PCs and GPS units, AutoCAD Map for the IWMDs and ArcGIS for the directorates.

The information systems were established to provide reliable sustainable computerized systems at the district level. Three major steps were taken:

1. Install computer hardware and software at the 27 IWMDs and five directorates;
2. Install IWMD water resources tabular databases at all the IWMDs;

3. Assign and train staff members from the IWMDs and directorates on computer basics, hardware maintenance, and database operations.

<u>Hardware and Software</u>

To introduce the computerized information systems at the IWMD, the first step was to provide needed computer equipment. The equipment for building the data management system was identified as follows:

At integrated districts level: desktop computers and peripherals with Windows XP, Office 2003, and Antivirus software, UPS and voltage stabilizers, Color printer, black and white printer, and local area network (LAN).

At Directorate level: desktop computers and peripherals with Windows XP, Office 2003, and Antivirus software, laptop, ArcView 9.2, UPS and voltage stabilizers, plotters, printes, scanners, LAN, USB mobile hard drives, DSL Internet connections.

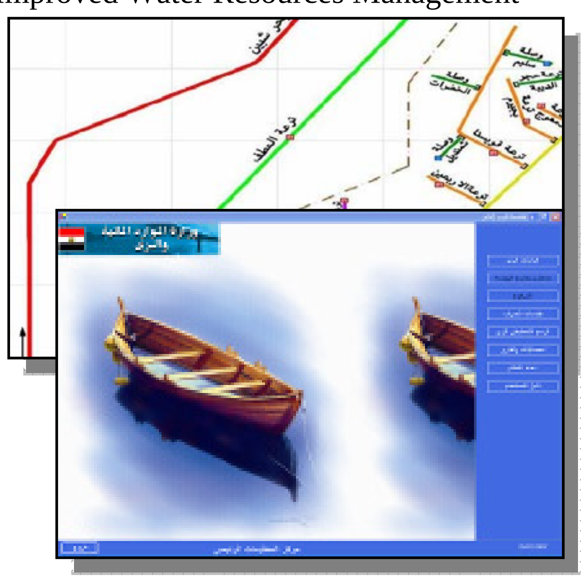
<u>IWMD Databases</u>

The six databases that were designed, constructed, and implemented at 27 IWMDs to provide timely data and information are: Water Level Database, Matching Irrigation Supplies and Demand (MISD) Database, Water Quality Database, Groundwater Database, Complaint Database, Violation Database.

The following presents a brief description of each of the six databases:

<u>Water Level Database</u>

The Water Level Database was originally prepared by the MWRI Information Center (MIC) under the Red Sea Sustainable Development and Improved Water Resources Management Project. It was updated in mid-2005 and upgraded again to the latest version (3.0) that was issued in August, 2006. The Water Level Database is a data management tool that archives, analyzes, and reports water levels for different sites. All of the canals were coded and tabulated as a part of the database. The paper register for the water levels from each IWMD were used to identify the number of sites required and located on the schematics of the database. The database has been customized for each IWMD with a canal schematic and dots for gauging sites. A user can click a canal on the schematics and enter the canal details and daily water levels via pop-up forms. Currently, water



levels at major control points within the IWMDs are collected three times a day (6:00 AM, 12:00 PM and 6:00 PM) and are recorded in a paper register and the database.

The figure below illustrates the main screen of the Water Level Database and the schematics for the canal network in an irrigation district (Captured from MIC Manual).

The Water Level Database exports specific data as shown below for use in the canal structure calibration worksheet by each IWMD.

Data Items for Canal Structures

	Arabic	English		
General Directorate			GD ID	
District			District ID	
Site Name			Site Code	
Structure Type			Structure Code	
Weir Crest Level				
Canal Name			Canal Code	
Canal Length				
Ave. Canal Width				
Reach Length				
No. of Gates				

	Gate 1	Gate 2	Gate 3	Gate 4	Gate N
Gate Width					
Bed Level					
Max allowable U/S					
Min Allowable U/S					
Max allowable D/S					
Min Allowable D/S					

Date	U/S Water Level (L1)	D/S Water Level (L2)	D/S Water Level from Weir (L3)	Total Gate Opening	Next Gauge Level (L4)

Data Items for Pump Stations

Data Item	Arabic	English		
Site Name			Site Code	
Structure Type			Structure Code	
Canal Name			Canal Code	
Canal Length				
Reach Length				

	Unit 1	Unit 2	Unit 3	Unit N
Pump Capacity				

				Unit 1		Unit N	
Date	U/S Water Level (L1)	D/S Water Level (L2)	Next Gauge Level (L4)	Hours	Q	Hours	Q

Data Items for Canal Network

	Arabic	English		
General Directorate			GD ID	
District			District ID	

Canal ID	Canal Name (Arabic)	Canal Name (English)	Canal Level/Rank
1-65	[illegible]		1
1-65-1	[illegible]		2
1-65-2	[illegible]		2
1-62-1	[illegible]		2
1-62-1-1	[illegible]		3
1-62-1-2	[illegible]		3
1-62-1-3	[illegible]		3
1-62-1-4	[illegible]		3
1-62-1-4-1	[illegible]		4
1-62-1-4-2	[illegible]		4

Data Items for Drainage Network

Drain ID	Drain Name (Arabic)	Drain Name (English)	Drain Level/Rank

The calibration worksheet developed by the IWRM project is based on six equations as follows:

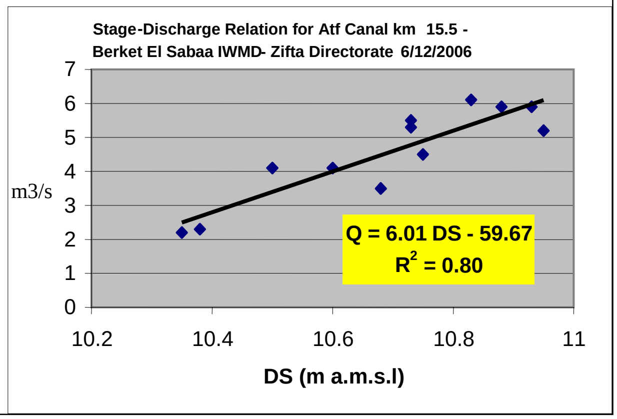
Order	Type of formula	Detailed	Needed data	Constants to be calibrated	Usual values
1	Weir	$Q = c \times H^n$	upstream water level	c, n	n around 1.5
2	Orifice	$Q = c_d A_o \sqrt{2gH}$	upstream and downstream levels of the of gate, gate opening A_o	c_d	c around 0.6-0.8
3	Manning (slope-area method)	$Q = \frac{1}{n} A R^{\frac{2}{3}} S^{0.5}$	Reach length, water levels at head and tail of the reach, cross section data; bed level, side slopes, bed width	$\frac{1}{n}$	$\frac{1}{n} \equiv 20$ - 40 for alluvial canals $\frac{1}{n} \cong 60$ for lined canals
4	Simplified Manning	$Q = kh^{\frac{5}{3}} (L_1 - L_2)^{0.5}$	Reach length, water levels at head, L_1,and at tail of the reach, L_2, bed level, F $h=L_1-F$	K	localized
5	Stage-discharge	It takes different forms: i) Power $Q = a\ h^b$ ii) polynomial $Q = c_1+c_2\ \mathbf{h}+c_3\mathbf{h}^2$	water level (or water depth), **h**	a,b for power formula and, c_1, c_2, c_3 for polynomial	b around 1.3-1.8
6	Linear stage-discharge (for small range of water levels)	$Q = a + b\ \mathbf{h}$	water level, **h**	a,b	localized

The following figure shows a sample of the calibration curve and data that had been provided by the Berket El Sabaa IWMD.

Flow Measurement on Atf canal

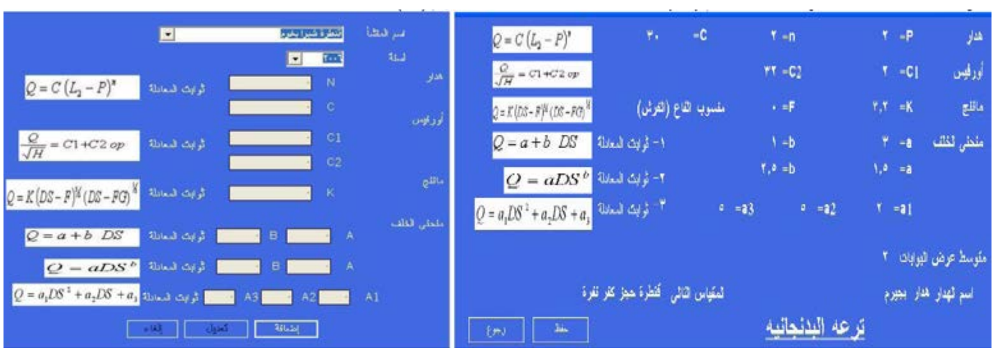
Site	Km 15.5	
Area Served (feddans)		number of gates
Canal Length (m)		gate width (m)
Reach Lenth (m)		invert level (F)
Average Canal Width (m)		

Date	dswl	Q (m3/sec)
23/5/2005	10.68	3.34
6/5/2005	10.75	4.5
29/6/2005	10.93	5.9
19/7/2005	10.73	5.5
21/7/2005	10.88	5.9
21/8/2005	10.83	6.1
3/9/2005	10.73	5.3
10/9/2005	10.6	4.1
23/10/2005	10.35	2.2
8/11/2005	10.95	5.2
8/12/2005	10.38	2.3
17/12/2005	10.5	4.1
5/1/2006	10.68	3.5



Each one of the sites was assigned with a rating equation based on the availability of the water level data for that site. A correlation relation was established based on one year water level historical data. The calibrated equations for the sites were then entered into the Water Level Database and discharge information was automatically calculated by the database based on the rating equations.

The following figures show the screen for different coefficients on specific sites (Captured from MIC Manual).



Matching Irrigation Supply and Demand Database (MISD)

As the Egyptian Ministry of Agricultural and Land Reclamation (MALR) was applying a policy of free cropping for farmers it was difficult to determine actual water demand, which led to a variance between water supply and demand that subsequently led to a shortage of water supply in some Districts and an excess of water supply in others.

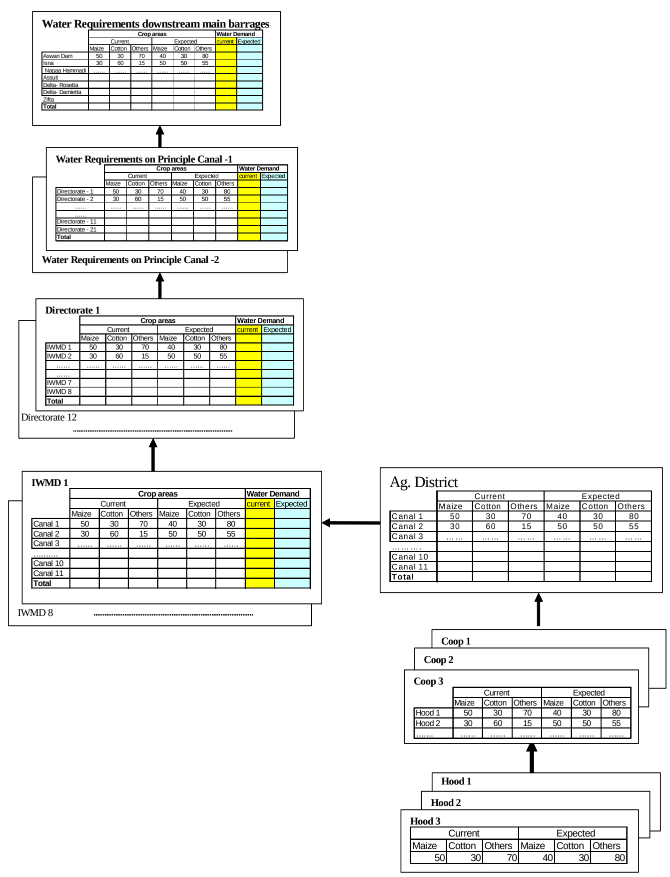
As the Egyptian MALR collected cropping information from farmers via field agents, it was decided that sharing this information with the Egyptian MWRI would be helpful in estimating water demand based on actual cropping patterns. In 1999, the MISD process had been initiated and was implemented in four pilot districts, followed by another 26 districts. Currently, about 100 districts, or about half of the total command area in Egypt, are applying the MISD process in their water management program.

The basic/preliminary arrangements for MISD implementation are; 1) formation of district joint committees; 2) adjustment and verification of the gross command area; 3) definition of the main crops for which to collect data; 4) crop data format; 5) type of data; 6) databases.

In terms of operation of the MISD, every two weeks the following activities are carried out:
MALR Extension agents collect crop areas and crop calendar for each Hood (Agricultural land parcel).

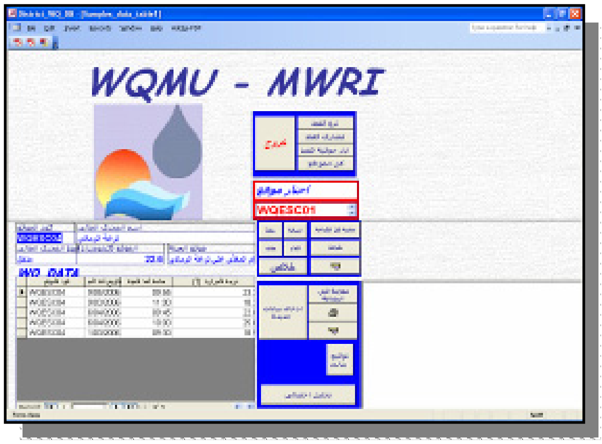
1. Crop data are sent to the Director of the Ag. Cooperative (village level) who compile the data within the Cooperative area.
2. Crop data are then sent to the Director of the Agricultural District for compilation and reconfiguration to match the irrigation command area and transmittal to the Irrigation District.
3. In the Irrigation District, crop data for current and next 15-day periods are used to calculate the biweekly water requirements for the district.
4. Biweekly crop data and water requirements are compiled at the Irrigation General Directorate, and sent first to the regional Water Distribution General Directorate and then to the Central Directorate for Water Distribution in Cairo.

The shown figure illustrates crop and water requirements data flow for the MISD process (Captured from MISD Guideline):



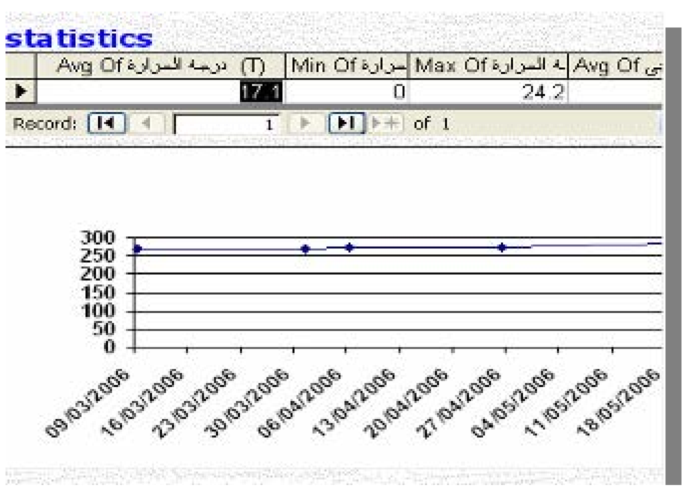
Water Quality Database

A water quality monitoring network was created at each IWMD. The average number of water quality sites per District is 15. Four parameters are measured, such as pH, BDO, Salinity, and temperature. The items are measured by using portable devices provided by the IWMD project. It was necessary to find a suitable method to manage all the collected water quality data for each District. The Water Quality database was prepared by the Water Quality Unit (WQU) through a Dutch-funded project and is currently used to store, analyze, display, and report water quality issues data in Egypt._The following figure shows the main screen for the Water Quality Database:

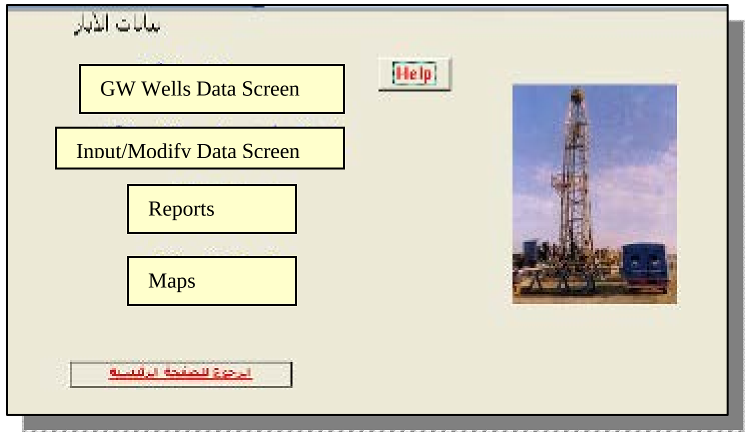


Using the Water Quality Database, new water quality locations can be added; sites can be retrieved by type (canal, drain, GW Well, or all types); quality data can be retrieved by site, by date, and/or by parameter. The user can also execute a statistical analysis using the stored data (average, Minimum, Maximum…etc).

The following figure shows an example of output:



Groundwater Database



A well inventory process was introduced to survey all the groundwater wells within each IWMD. The Groundwater Database includes all the parameters required to identify a groundwater well, starting from its location (GPS latitude and longitude) and to other technical data as shown in the table below.

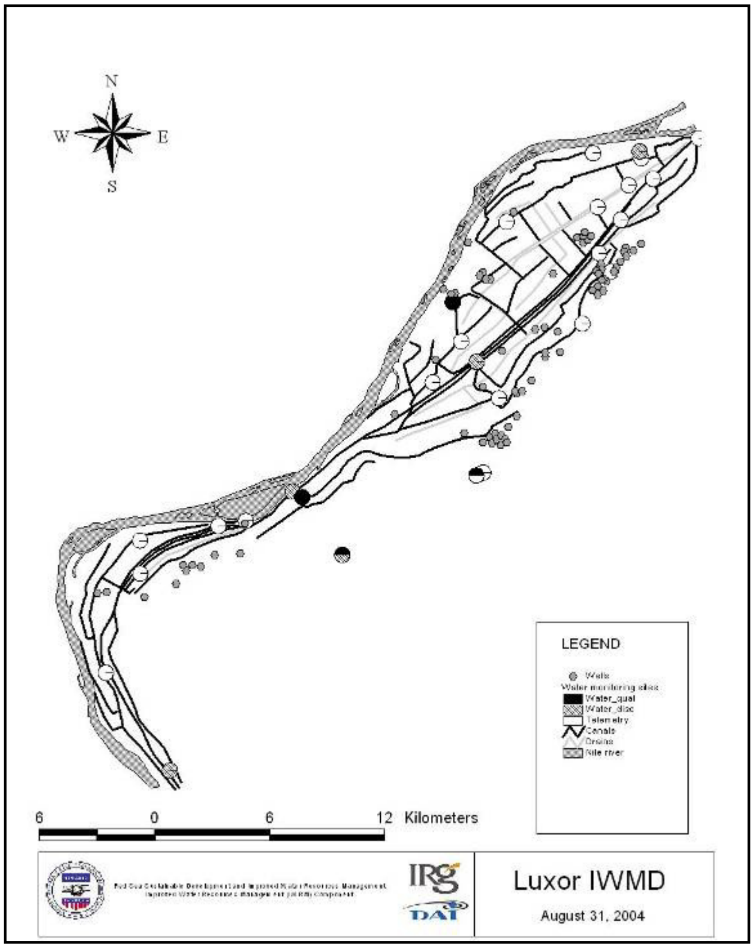
The Groundwater Database was originally developed by the Groundwater Sector within the MWRI. It was then customized for IWMDs based on a request from the IWRM project.

The following table illustrates data found n the Groundwater Database:

1	Owner Name	12	Source Of Power
2	Well Construction Date	13	Operating Hours
3	Well Coordinate	14	Discharge
4	No. Of Wells	15	Type Of Pump
5	Well Use	16	Nearest Well Distance
6	Area Served	17	Nearest Water Way Distance
7	Well Diameter	18	Salinity
8	Type Of Pipes	19	Do
9	Total Depth	20	Ph
10	Screen Depth	21	Temperature
11	Sand Trap Length	22	Static Depth

The database can print standard and ad-hoc reports to meet IWMD requirements, and can also export groundwater data to an Excel worksheet. Additionally, the database can display the location of wells over a base map using Arc Explorer (which is free to download).

A sample of a map with GW wells shown for the Luxor IWMD is shown below:



<u>Complaints Database</u>

The Complaint Database is designed and constructed by MIC (the Ministry Information Center). A complaint can be stored in the Complaint Database based on weather if it is a technical or administrative complaint. All complaints should have specific fields, such as the name of complainer, date, and type of complaint. A tracking field should also be appended in order to track whether the complaint has been resolved how it was resolved.

Violation Database

MIC also provided the Violation Database, which is used for tracking and archiving violations. The database was designed to deals with Law No.12 - 1983, and Law No.48 - 1982. The system records proceedings in which the violations are written (responsible engineer's name, location, day, date, subject, violator's name, etc.). The system also tracks each violation with all its stages (warning, removal, court, Jurisdictional verdict). It generates various reports such as contraventions' statistics report and district name report.

Digital Mapping System

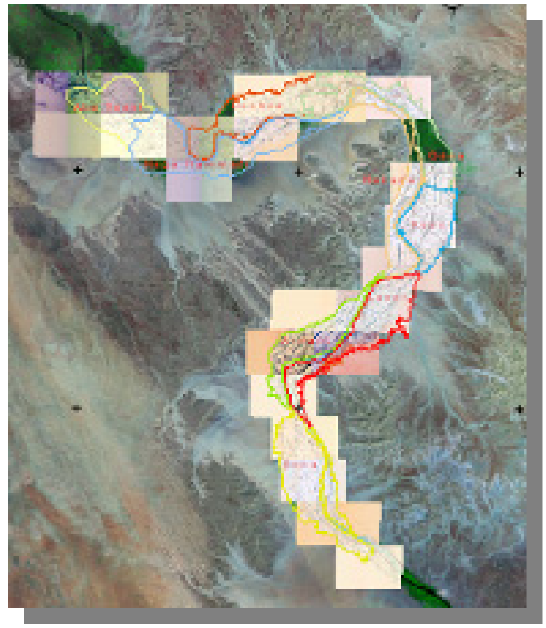
The digital mapping system development consists of four major activities: 1) Base map development; 2) Boundary demarcation; 3) Physical system delineation; 4) Branch canal delineation.

The following presents a brief description of each activity:

Base Map Development

A set of 1:25,000 and 1:50,000 scale paper maps covering each IWMD area were purchased from the ESA and distributed to the IWMDs. The 1:25,000 maps were scanned and geo-referenced using ArcGIS (The Egypt Red Belt is the coordinate system used for the NSA. WGS 1984 UTM 36 N is another commonly used coordinate system for Egypt), producing a set of raster images (geo-tiff format) for each IWMD. AutoCAD MAP is commonly used in Egypt by engineers. With it, a process of choosing a geographic coordinate system and importing both the geo-tiff 1:25,000 maps and the clipped satellite imagery were carried out to create the base map for each IWMD.

Boundary Demarcation



A ministerial decree was issued to define the IWMD boundaries based primarily on hydrological boundaries and satellite imagery (NASA Landsat 7 ETM+). Boundary delineations are based on ministerial decree and the well knowledge of the water distribution engineers in each IWMD. A team from each district consists of the staff members who are most familiar with the districts and villages that have sketched the new ministerial decree boundaries for their districts on the 1:25,000 paper maps. The new sketches were scanned, geo-referenced, and traced on-screen to create a district boundary file for each IWMD via ArcGIS. The IWMD boundary shapefiles containing the new boundary information were sent to the IWMDs for verification and revision, and then the final IWMD boundaries were delineated.

Physical System Delineation

The physical system of each IWMD consists of canals, drains, district boundary, water flow monitoring sites, water quality monitoring sites, groundwater wells, water structures (regulators, Weirs, Pump stations…etc.), and BCWUA locations

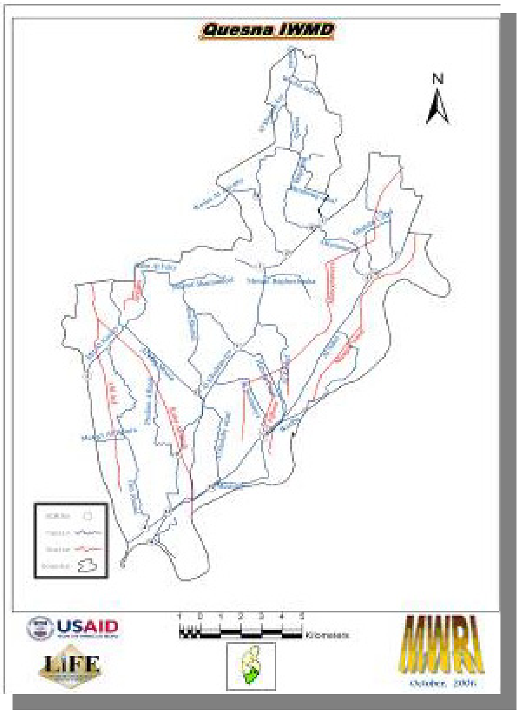
The shape files for the IWMD boundary were imported to AutoCAD Map. Using the technique of on-screen digitizing using the base map layer, all waterways (canals and drains) were delineated. Using a GPS device all the locations of the water monitoring sites (quality and quantity) were captured, downloaded to a PC using free DNR Garmin software then imported to AutoCAD MAP.

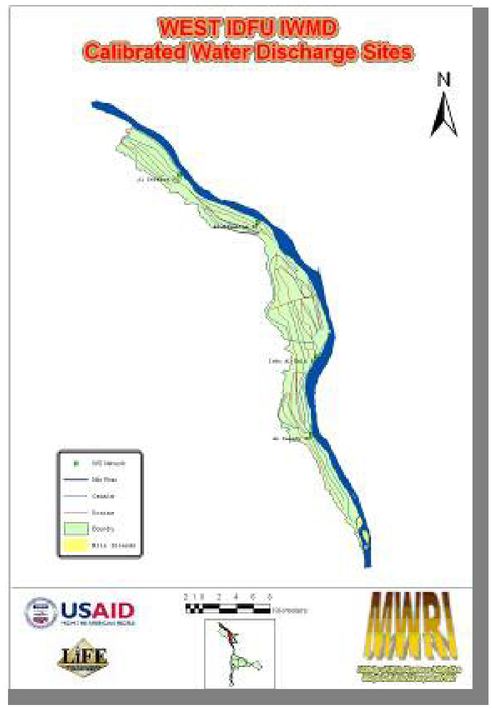
For groundwater well locations, the Groundwater Database creates shapefiles automatically and imports them as the GW layer in AutoCAD MAP.

Additionally, a set of processes were made to link the features drawn in AutoCAD MAP to a tabular table using the database connection in AutoCAD MAP to Microsoft Excel, Access, or txt files.

A set of standard map layouts was set for all the IWMD maps including the legend, north direction, title bar, scale bar and frame.

Two IWMD maps using one of the standard layouts are shown below.





Branch Canal Boundary Delineation

A discrepancy was detected between the gross area served by each IWMD in the ministerial decree and the calculated area based on its digital IWMD boundary using ArcGIS. The calculated areas ranged from 10% less to 160% more than the decree areas. Some of the main issues with the differences between the decree and GIS areas are:

- Urban, industrial and other non-agricultural areas were included.
- Unofficial, hilly/out of command, and underdeveloped/new lands were included.

To obtain with good accuracy of agricultural area served by branch canal will help improve the calculation of crop water requirements and the distribution of water resources. Ultimately this will also improve the matching between irrigation demand and supply.

In order to determine the exact irrigable area for each IWMD, a survey of branch canal irrigable area was carried out. For each branch canal, the area served was defined as the total land that is officially registered with the MALR with water supplied from the same branch canal for crop production. Fallow lands (i.e. lands not irrigated this year or this season but irrigated the year before) were included.

Pre-Survey. With branch canals from the digital map and handout based on knowledge of the districts to draw the branch canal boundaries, canals, drains, boundaries, and landmarks were downloaded to the GPS units and used as guide during the field work.

Field Work. Visited the questionable locations, asked farmers to verify which plot is irrigated by which canal when there is a doubt. Correct the boundaries on the map.

Once sure of the boundaries, used the GPS track function and circle around the boundary area. Went back to the starting point to close the boundary line, and saved the track on the GPS device. Then, GPS built-in area function calculated the track area to provide a first estimate of the branch gross command area. The detailed methodology used by the IWMD mapping teams is discussed below.

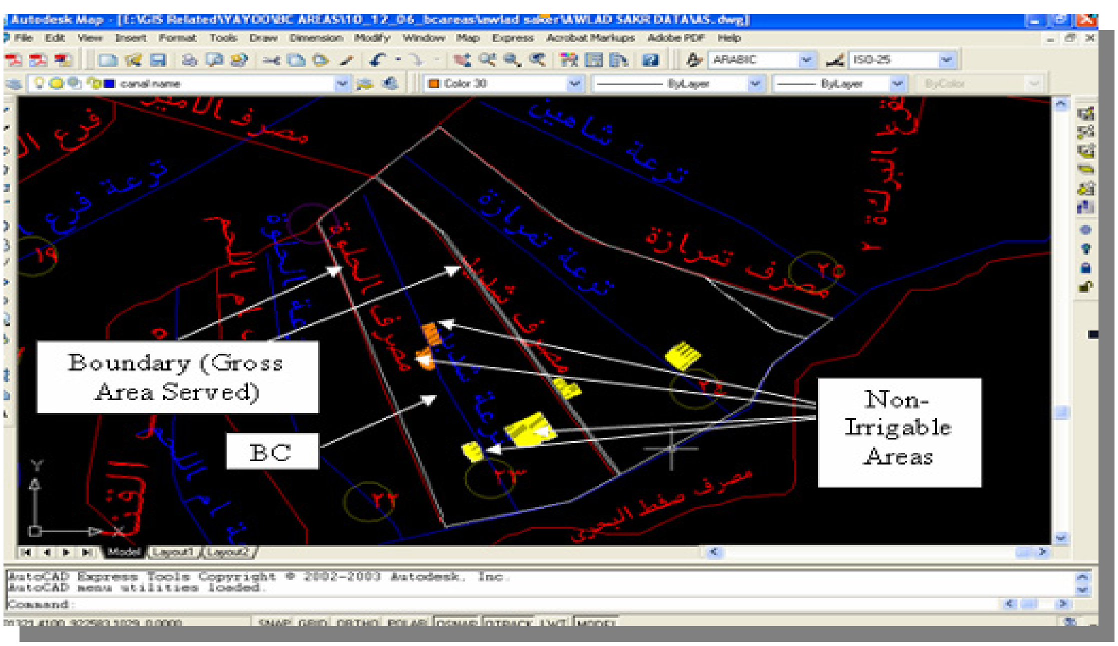
Post-Survey. Connected the GPS device to the computer with the DNR Garmin software, import the tracks to AutoCAD Map from the GPS devise via the Garmin software and saved these tracks as shapefiles.

The IWMD staff added the boundaries/tracks on the 1:25,000 base maps. On the screen, the branch canal boundaries were checked for their accuracy, i.e. that they matched with known landmarks. Then, the staff used the 'list' command to calculate the branch canal gross command area.

Using the clipped satellite image, Google Earth image, and the GPS device, the IWMD team determinates the non-irrigable areas. Then the net area for each branch canal can be calculated based on the following table:

Feeder canal	Branch canal	Main boundaries	Gross area (fed)	Non-agricultural areas (fed)	Net irrigable area (fed)

An example of the branch canal command area survey is shown below.



The irrigable area for Sheded canal is calculated based on the GPS survey results as show below.

Feeder canal	Branch canal	Main boundaries	Gross area (fed)	Non-agricultural areas (fed)	Net irrigable area (fed)
Deffan	Sheded	Mosque at village 8 Al Hamra	1693.47	65.54(residential) + 29.16 (water way)	1598.77

LESSONS LEARNED

Identification of lessons learned from any endeavor is an extremely valuable exercise, and is imperative n this instance considering IWMD activities will be continued by the MWRI. The following lessons learned are the result of an attempt to objectively identify items worthy of consideration when establishing and implementing information systems at the MWRI district and directorate levels.

1. Introducing central-level MWRI databases at the district is a way to get the district information systems up and running quickly.
2. The IWMDs were a bit overloaded with six databases in the initial stage of the project. In the future, a phased approach should be implemented to introduce two or three of these databases every four to six months.
3. A database management system is appropriate for the IWMDs and has provided them with the essential tools to store, analyze, and report water resource data in a timely fashion. The District managers are now able to make water management decisions based on “real” data.
4. A digital mapping system has produced up-to-date high-quality maps including boundary, canals, drains, water monitoring points, water quality sampling points, wells, BCWUA locations, and branch canal command areas for each District. With GPS units and AutoCAD Map, the Districts have inexpensive tools to measure irrigable areas accurately.
5. IT technical support was weak from each of the Directorates. All future training courses should include the Directorate staff members.
6. Interactions between MWRI central offices and the IWMDs were useful, and have provided an exchange of experience and ideas as well as a better understanding of district information system needs.
7. Output results of the MISD database (i.e., biweekly water demands) are questionable in some cases because the database contains a hardwired system target efficiency factor of 70% and is not calibrated for each IWMD.

RECOMMENDATIONS

The objectives of the IWMD program in the Egyptian water sector were to modernize water management systems and decentralize parts of the system, while developing capacity to manage new authorities at lower levels. These objectives were well served as a result of the IWRM achieving a great deal of success in the information systems at the 27 districts and five directorates.

Data collection and management are the foundation of all aspects of water management. Applications range from resource availability assessment to the allocation of water to productive activities in various sectors as mandated in the IWMD program. Integrated water management at the district level is a critical and important empowerment and devolution process. This process not only informs national and regional decision makers regarding key water management issues at the districts, but it empowers the district staff, water users, and other local stakeholders to actively participate in the improvement of water management in their immediate surroundings.

Robust systems of information management have been started and data are being entered into modern information systems to support district-level management decision making and routine data communications with higher MWRI levels. The momentum built under the IWRM should be maintained and expanded, and the information systems and procedures that have been developed and implemented by the IWRM project should be extended to all 204 districts and 22 directorates to facilitate devolution of centralized authority from the national level.

The information systems need to be introduced and implemented at the directorate to consolidate district data via direct PC modem communications or Internet in the near future. To prepare for this recommended distributed information management approach, all the information systems at the directorates should have the functionality to access, append, and consolidate data/information from the remote computers in the districts, and to provide district data and information to MWRI in Cairo. A majority of the IWMD databases can be implemented by the directorates with some minor modifications. Under the IWRM project, the information system development work should be mainly focused on the five directorates to establish the distributed information system over the next 24 months.

DECISION-SUPPORT SYSTEMS FOR EFFICIENT IRRIGATION IN THE MIDDLE RIO GRANDE

Ramchand Oad[1]
Kristoph-Dietrich Kinzli[2]
Nabil Shafike[3]
David Gensler[4]

ABSTRACT

Water is the lifeblood of the American West and the foundation of its economy, but it remains its scarcest resource. The explosive population growth in Western United States, the emerging additional need for water for environmental uses, and the national importance of the domestic food production are driving major conflicts between these competing water uses. Irrigated agriculture in particular is by far the largest water user of diverted water – 80% country wide and 90% in the Western U.S – and since it is perceived to be comparatively inefficient user, it is frequently asked to decrease its water consumption (Oad and Kullman, 2006). The case of the Middle Rio Grande illustrates the problem very well. The river is the ecological backbone of the Chihuahuan Desert region in the western United States, and supports its dynamic and diverse ecology, including the fish and wildlife habitat. The Rio Grande Silvery Minnow is federally listed as endangered species, and the irrigated agriculture in the Middle Rio Grande has come under increasing pressure to reduce its water consumption while maintaining the desired level of service to its water users. This paper will present our on-going research on options to make irrigation system operations more efficient in the Middle Rio Grande Conservancy District. Specifically, it will describe formulation and implementation of a Decision-Support System (DSS) that can assist the MRGCD managers to more efficiently plan and implement their water delivery operations, thereby reducing river diversions. Since year 2000, MRGCD has been modernizing their physical water delivery network, and the DSS will be used in tandem with SCADA software in making water delivery decisions based on real-time knowledge of available water supplies and crop water requirements. In irrigation systems, the conceptual problem addressed by the DSS is how best to route water supply in a main canal to its laterals so that the required water diversion is minimized. The MRGCD DSS uses linear programming to find an optimum water delivery schedule for canal service areas in the MRGCD irrigation system. For the past three years, the model has been validated in the field and the evaluation indicates that the model recommendations are realistic and represent ditch-rider practices.

[1]Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado; oad@engr.colostate.edu
[2]Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado; kkinzli@engr.colostate.edu
[3]Interstate Stream Commission, Albuquerque, NM; nabil.shafike@state.nm.us
[4]Middle Rio Grande Conservancy District, Albuquerque, NM; dgensler@mrgcd.com

INTRODUCTION

Irrigated agriculture in the Western United States has traditionally been the backbone of the rural economy. The climate in the American West with low annual rainfall of 20-38 cm is not conducive to dry land farming. Topography in the West is characterized by the Rocky Mountains which accumulate significant snowfall, and the peaks of the snowmelt hydrograph are stored in reservoirs allowing for irrigation throughout the summer crop growing season.
Of the total available surface water irrigated agriculture uses roughly 80 to 90% (Oad and Kullman, 2006).

The combined demands of agriculture, urban, and industrial sectors in the past have left little water for fish and wildlife. Since irrigated agriculture uses roughly 80 to 90% of surface water in the West, it is often targeted to decrease diversions. Due to wildlife concerns and demands from an ever growing urban population, the pressure for flow reductions on irrigated agriculture increases every year. In order to sustain itself and deal with external pressure for reduced river diversions irrigated agriculture has to become more efficient in its water consumption. This paper focuses on research regarding improving water delivery operations in the Middle Rio Grande irrigation system through the use of a decision support system.

Middle Rio Grande Valley

The Middle Rio Grande (MRG) Valley runs north to south through central New Mexico from Cochiti Reservoir to the headwaters of Elephant Butte Reservoir, a distance of approximately 175 miles. The MRG Valley is displayed in Figure 1.

The valley is narrow, with the majority of water use occurring within five miles on either side of the river. The bosque, or riverside forest of cottonwood and salt cedar, is supported by waters of the Rio Grande; the bosque being surrounded by widespread irrigated farming. The Cities of Albuquerque, Rio Rancho, Belen and several smaller communities are located in and adjacent to the MRG Valley. Although the valley receives less than 22 cm of rainfall annually, it supports a rich and diverse ecosystem of fish and wildlife and is a common outdoor resource for communities in the region. Water supply available for use in the MRG Valley includes: native flow of the Rio Grande and its tributaries, allocated according to the Rio Grande Compact of 1938; San Juan-Chama (SJC) project water, obtained via a trans-mountain diversion from the Colorado River system; and groundwater. Water is fully appropriated in the MRG Valley and its utilization is limited by the Rio Grande Compact, which sets forth a schedule of deliveries of native Rio Grande water from Colorado to New Mexico and from New Mexico to Texas (Rio Grande Compact Commission, 1997). Water demand in the MRG Valley includes irrigated agriculture in the Middle Rio Grande Conservancy District (MRGCD) Indian Lands, and municipal and industrial consumption. In addition to these demands, there are significant consumptive uses associated with the riparian vegetation, reservoir evaporation, and the river flow targets associated with two federally-listed endangered species, the Rio Grande silvery minnow (*Hybognathus amarus*), and the southwestern willow fly catcher (*Empidonax traillii extimus)* (USFWS, 2003).

Figure 1. Middle Rio Grande Valley (Barta, 2003)

<u>Middle Rio Grande Conservancy District.</u> The MRGCD was formed in 1925 in response to flooding and the deterioration of irrigation works (Shah, 2001). Water diverted by the MRGCD originates as native flow of the Rio Grande and its tributaries, including the Rio Chama. The MRGCD services irrigators from Cochiti Reservoir to the northern boundary of the Bosque del Apache National Wildlife Refuge. Irrigation facilities managed by the MRGCD divert water from the river to service agricultural lands, which include small urban parcels and large tracts that produce alfalfa, pasture, corn, and vegetable crops such as green chile which is famous throughout the Southwest. The MRGCD supplies water to its four divisions -- Cochiti, Albuquerque, Belen and Socorro -- through Cochiti Dam and Angostura, Isleta and San Acacia diversion weirs, respectively. Water is conveyed in the MRGCD by gravity flow through primarily earthen ditches. On-farm water management is entirely the responsibility of water users and application is typically surface (flood) irrigation, either basin or furrow. The MRGCD does not meter individual farm turnouts, and ditch-riders estimate water delivery on the basis of time required for irrigation. Therefore, the quantity of water applied to fields is not measured.

During the recent drought years, low flows combined with flow requirements for the endangered Rio Grande Silvery Minnow have drastically reduced available water supplies. In order to deal with reduced water availability, the MRGCD has taken a proactive approach to be a more efficient water user and service its irrigators with reduced river diversions. Towards this end, the division managers and ditch-riders are increasingly practicing scheduled water delivery, which is an effective way to fulfill demand with reduced available water.

Scheduled Water Delivery (SWD) is used in irrigation systems worldwide to improve water delivery and to support water conservation. In SWD, lateral canals receive water from the main canal by turns, allowing water use in some laterals while others are closed. In addition to this water scheduling among laterals, there can be scheduling within laterals whereby water use is distributed in turns among farm turnouts along a lateral. By distributing water among users in a systematic scheduled fashion, an irrigation district can decrease water diversions and still meet crop water use requirements.

Decision Support Modelling of Irrigation Systems

The New Mexico Interstate Stream Commission and the MRGCD have sponsored a research project with Colorado State University to develop a decision support system (DSS), to model and assist implementation of scheduled water delivery in the MRGCD's service area. A DSS is a logical arrangement of information including engineering models, field data, GIS and graphical user interfaces, and is used by managers to make informed decisions. In irrigation systems, a DSS can organize information about water demand in the service area and then schedule available water supplies to efficiently fulfill the demand.

The conceptual problem addressed by a DSS for an irrigation system, then, is: how best to route water supply in a main canal to its laterals so that the required river water diversion is minimized. The desirable solution to this problem should be "demand-driven", in the sense that it should be based on a realistic estimation of water demand. The water demand in a lateral canal service area, or for an irrigated parcel, can be predicted throughout the season through analysis of information on the irrigated area, crop type and soil characteristics. The important demand concepts are: When is water supply needed to meet crop demand (Irrigation Timing), How long is the water supply needed during an irrigation event (Irrigation Duration), and How often must irrigation events occur for given service area (Frequency of Irrigation).

Decision support systems have found implementation throughout the American West and are mostly used to regulate river flow. Decision support systems on the river level are linked to gauging stations and are used to administer water rights at diversions points. Although decision support systems have proved their worth in river management, few have been implemented for modeling irrigation canals and laterals (NMISC, 2006). The research presented in this paper has focused on developing, calibrating, validating and eventually implementing a decision support system capable of modeling flow on a canal and lateral level, with the overall goal of efficient irrigation water delivery.

FORMULATION OF DECISION SUPPORT SYSTEM FOR THE MIDDLE RIO GRANDE

The DSS was formulated using linear programming with the use of an objective function. Overall model structure consists of three modules that function in concert to calculate the most efficient irrigation water delivery.

Model Programming

Programming in the model was developed using an objective function to schedule water deliveries to lateral service areas. Constraints on variables within the objective function are specified and must be satisfied in determining the optimum solution. This process achieves the result that water delivery to laterals with more immediate water needs is favored, and delivery to laterals that have sufficient water in a given time step is minimized.

$$\text{Minimize } Z = MP_{D-0}\, X_{D-0} + MP_{D-1}\, X_{D-1} + MP_{D-2}\, X_{D-2} + MP_{D-3}\, X_{D-3}$$

where Z is the sum of a modified priority (MP) multiplied by amount of supply (X) from the dummy supply to each demand node. The subscripts refer to the nodal points between which flow occurs, i.e., X_{D-1} refers to flow from the Dummy supply to Check 1, and MP_{D-1} refers to the modified priority of demand to be satisfied at Check 1 from the Dummy supply node. The MP value reflects the need-based ranking system where demand nodes with lower available soil moisture are favored for irrigation. The objective function is solved in conjunction with a system of mass balance equations representing the actual water (and dummy water) delivered to demand nodes, along with other physically-based constraints. Figure 2 displays a schematic representing the model programming.

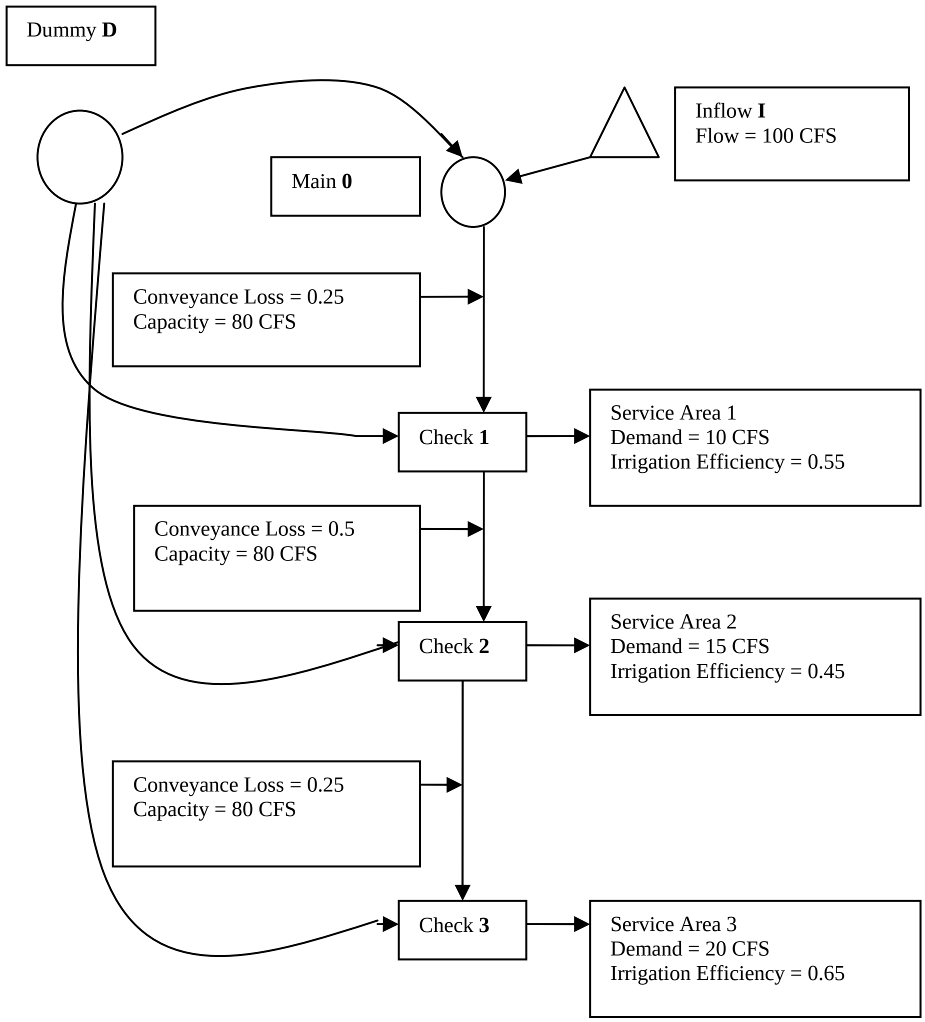


Figure 2. Schematic of Model Programming

Model Structure

The DSS consists of three elements; a water demand module, a supply network module, and a scheduling module. A Graphical User Interface (GUI) provides a means for linking the three elements of the DSS. This GUI constitutes a framework for the DSS that provides the user with the ability to access data and output for the system. The three DSS model components are termed modules. The project GIS and databases are used to develop input for both the water demand and the supply network modules. Some of the input is directly linked through the GUI and some is handled externally in this DSS version. Figure 3 displays the structure of the MRGCD DSS.

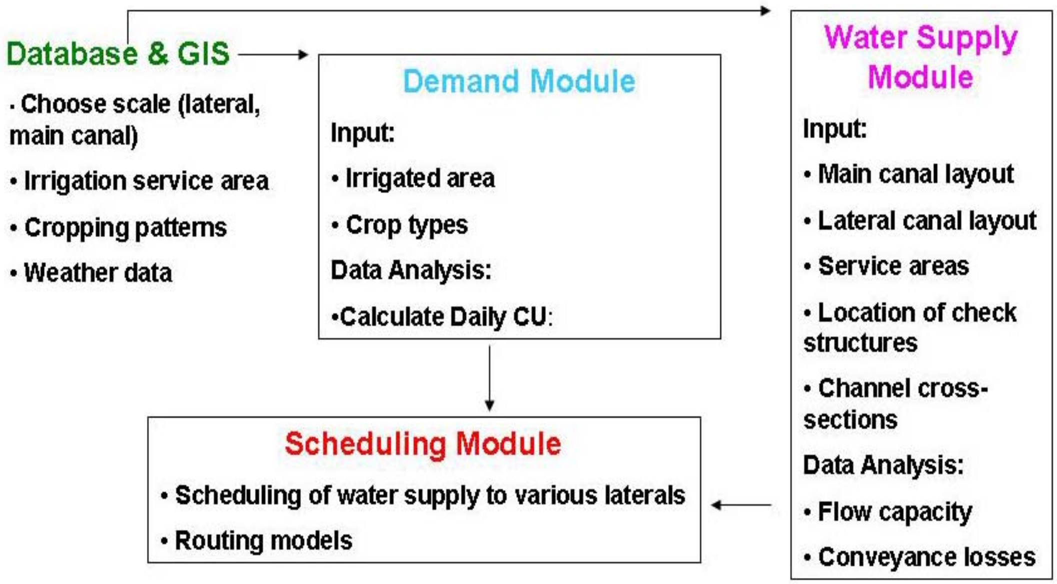


Figure 3. Model Structure Displaying the Three Modules

<u>Water Demand Module.</u> The water demand module of the MRGCD DSS is implemented through the Integrated Decision Support Consumptive Use, or IDSCU model, a model developed over a period of years at the Colorado State University. The IDSCU model consists of a Graphical User Interface (GUI) written in Visual C++ and program calculations implemented with FORTRAN. The IDSCU model offers numerous features and options and calculates the following: crop consumptive use (CU), crop irrigation requirement (CIR), and readily available moisture (RAM) as a capacity. The latter two variables, CIR and RAM, are subsequently used in the supply network module. Crop consumptive use is calculated using the Penman-Montieth Method. The reference ET is calculated using weather data from the MRGCD. Crop coefficients using growing degree days are applied to the Penman-based ET to obtain a consumptive use for each crop type throughout the growing season. The water demand module performs these calculations to obtain a spatially-averaged consumptive use at the lateral service area level, using the distribution of crop types within each service area.

The crop irrigation requirement (CIR) is calculated by accounting for the effective precipitation using the Soil Conservation Service Method .The crop irrigation requirement is calculated on a daily basis, corresponding to the water needed to directly satisfy crop needs for all acres in the service area. The crop irrigation requirement for the service area is subsequently passed to the supply network module, where it is divided by an efficiency factor to obtain a lateral service area delivery requirement (LDR).

Based on acreages, crop types and soil types within each lateral service area, a RAM is calculated. The RAM calculated in this context represents a storage capacity to be filled and depleted over several irrigation cycles during the course of the irrigation season. During each irrigation, it is expected that an amount of water equal to the RAM will be stored in soils which is then is depleted, due to crop water use.

Supply Network Module. The supply network module represents the layout of the conveyance system, its physical properties, supply to the conveyance network, and the relative location of diversions from the network to the lateral service area. The layout of the conveyance system is specified through a user-designed link-node network. Through the DSS GUI, a user can drag and drop different types of nodes such as inflows, demands and return flow nodes. The link-node network represents the connections between canals or laterals and demands for water at each service area.

Irrigation Scheduling Module. The irrigation scheduling module can be used to plan water deliveries to meet crop demand at the lateral and at the main canal level. The module calculates and displays a schedule for the laterals on a given main canal. This schedule indicates how many laterals can be run at a time, how long each lateral should run and how often. The module is currently set up to run on a daily time step. This module calculates the daily irrigation schedule using mass balance equations and the linear programming solver. The approach is based on the consideration that the farm soil root-zone is a reservoir for water storage, for which irrigation applications are inflows and CIR is an outflow.

MODEL FIELD TESTING AND IMPLEMENTATION

A research collaboration between the MRGCD, the New Mexico Interstate Stream Commission and Colorado State University has supported the DSS project since 2004. During this time, calibration and field testing have been conducted to improve the performance of the DSS.

Field Data Collection and Calibration

Data files were initially developed for each main canal and its laterals by collecting the following information: cropped acreage, crop type, and soil type by lateral service area. The water holding capacity of the soil in each lateral service area was determined using GIS and SSURGO soil maps. System infrastructure data were also collected to insure accurate representation of the distribution network. Canal capacity measurements were made to represent actual canal carrying capacities in the DSS. To calibrate the model, a sensitivity analysis was performed on the main input variables. Sensitivity analysis consisted of varying one single variable while keeping all other variables constant. Using the sensitivity analysis the model input parameters were calibrated.

Field Testing

To test the model prediction capability, the model was run in operational mode using 2006 water supply, weather, and crop area data. The readily available moisture (RAM) at the beginning of the season was set at zero. The RAM at the start of a delivery schedule was also set to zero in order to utilize the entire available soil moisture. The irrigation efficiency and the return flow percentage were both set at 50%, based on the results of previous sensitivity analysis and our review of the literature. The irrigation schedule recommended by the DSS model for 2006 was compared to the actual water delivery practice of ditch-riders in 2006. The irrigation duration, irrigation frequency (time between irrigations) and irrigation flowrate during an irrigation season from the model were compared to data collected in the field over a period of three years. The field data obtained from ditch-riders consists of mean irrigation duration, mean irrigation frequency, and mean irrigation flowrate. Figures 4, 5, and 6 display the comparison of irrigation duration, irrigation frequency and irrigation flowrate for the 2006 irrigation season respectively. Table 1 displays the comparison between the DSS and actual practice for mean irrigation duration, mean irrigation frequency and mean irrigation flowrate.

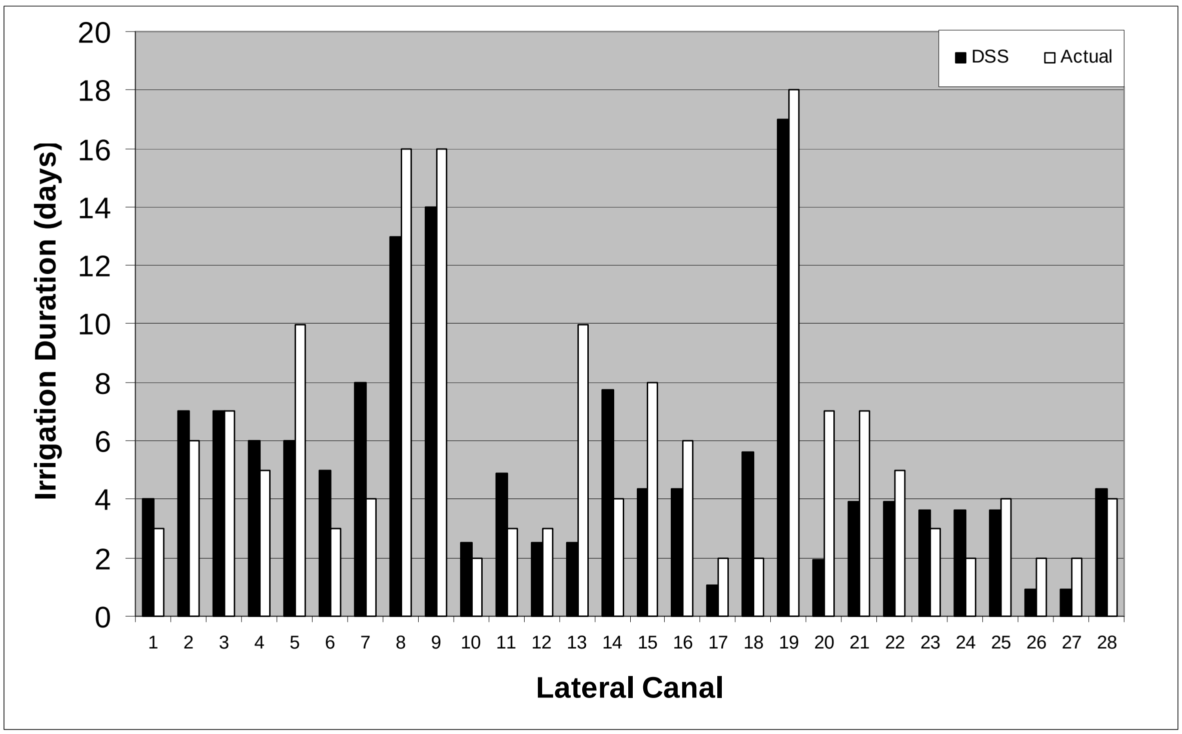


Figure 4. DSS Irrigation Duration compared to Actual Irrigation Duration for 28 Laterals in 2006

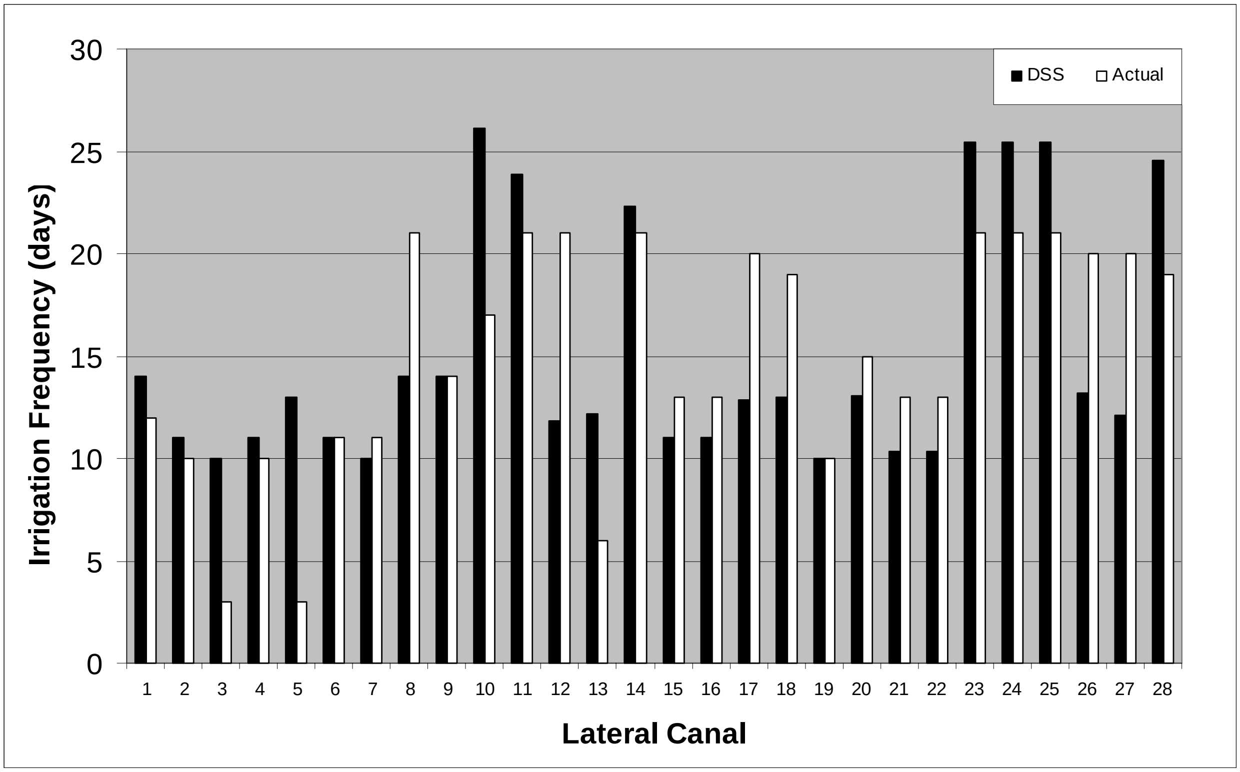


Figure 5. DSS Irrigation Frequency compared to Actual Irrigation Frequency for 28 Laterals in 2006

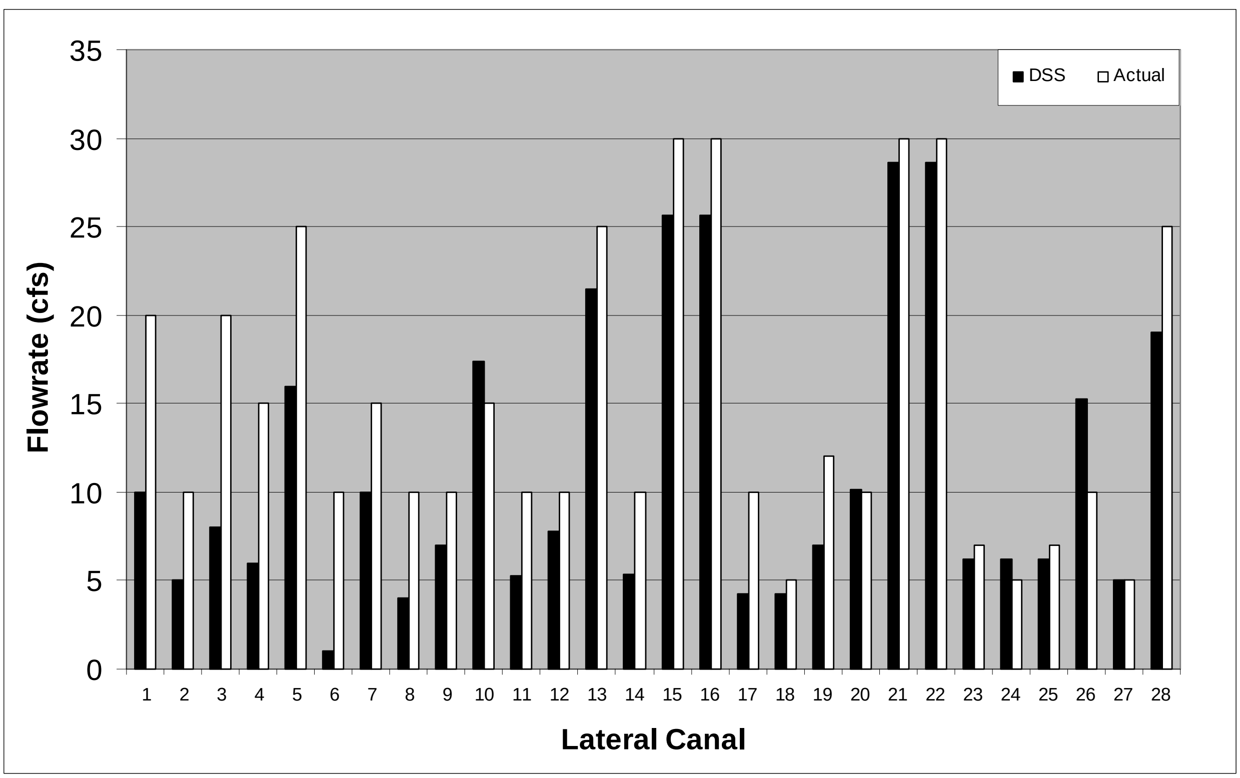


Figure 6. DSS Flowrate compared to Actual Flowrate for 28 Laterals in 2006

Table 1. Comparison between the DSS and Actual Practice for Mean Irrigation Duration, Mean Irrigation Frequency and Mean Irrigation Flowrate.

Irrigation Duration (days)

Year	Mean DSS Recommendation	Mean Ditch-rider Practice	Difference
2004 (2 Laterals)	4.41	3.50	-0.91
2005 (2 Laterals)	2.85	3.10	0.26
2006 (28 Laterals)	5.34	5.86	0.52

Irrigation Frequency (days)

Year	Mean DSS Recommendation	Mean Ditch-rider Practice	Difference
2004 (2 Laterals)	13.85	16.00	2.15
2005 (2 Laterals)	15.13	16.00	0.88
2006 (28 Laterals)	15.07	14.96	-0.10

Irrigation Flowrate (cfs)

Year	Mean DSS Recommendation	Mean Ditch-rider Practice	Difference
2004 (2 Laterals)	6.49	9.00	2.52
2005 (2 Laterals)	5.89	9.50	3.62
2006 (28 Laterals)	11.30	15.04	3.73

Irrigation duration comparison results are acceptable for most laterals but large discrepancies exist between the model and the actual practice on a significant number of laterals. This could be due to several reasons. First, the information obtained through the ditch-rider interviews is quite subjective and might not reflect the actual irrigation practice. Second, the irrigation practice used by ditch-riders could be inappropriate which is indicated by the irrigation durations being either too short or too long. The fact that the 2006 irrigation season was the first time several ditch-riders practiced scheduled water delivery could explain the difference between the optimal duration represented by the DSS and the actual duration used in practice. Ditch-riders currently do not have soil moisture probes that can be used to indicate the need for irrigation and their schedules are often arbitrary. The laterals with significant discrepancies warrant further investigation to determine if the model recommendations are reasonable or if the ditch-riders' practices need change.

DSS Model values for irrigation frequency were slightly longer than the values obtained from the ditch rider practice, and large discrepancies exist between the model and the actual practice on a significant number of laterals. The reason for this could be that in actual practice, irrigation events occur before the soil moisture (RAM) is significantly depleted. Field observations during the 2005-06 irrigation seasons show that alfalfa fields were irrigated every ten days, which is excessive and would account for the shorter irrigation frequency recorded from the field data.

Irrigation frequencies that are longer than the DSS recommendation indicate that the crops are possibly being stressed.

The actual flow rate proved to be significantly larger than the model recommendations. This is due to the fact that gauges do not exist on most canals and the flow rate given by the ditch-riders is at best an estimate. In the future, staff gages need to be installed on canals in order to develop stage-discharge relationships, or automated gates with flow meters need to replace aging lateral turnout structures.

When comparing the irrigation duration, frequency, and the required irrigation flowrate the results from the model compare well with the field data. Overall, the scheduled water delivery developed by the DSS is reasonable within the limits set forth by the MRGCD.

Using limited scheduled water delivery and infrastructural improvements, the MRGCD has been able to significantly reduce river diversions. Historically, the MRGCD diverted as much as 600,000 acre feet per year from the Rio Grande. Over the last 3 years, their diversions have averaged less than 350,000 acre feet per year. Figure 7 displays the decreasing trend in total MRGCD river diversions. Current schedules are not based on crop demand and rotation is only practiced in a few limited areas, leaving much room for efficiency improvement.

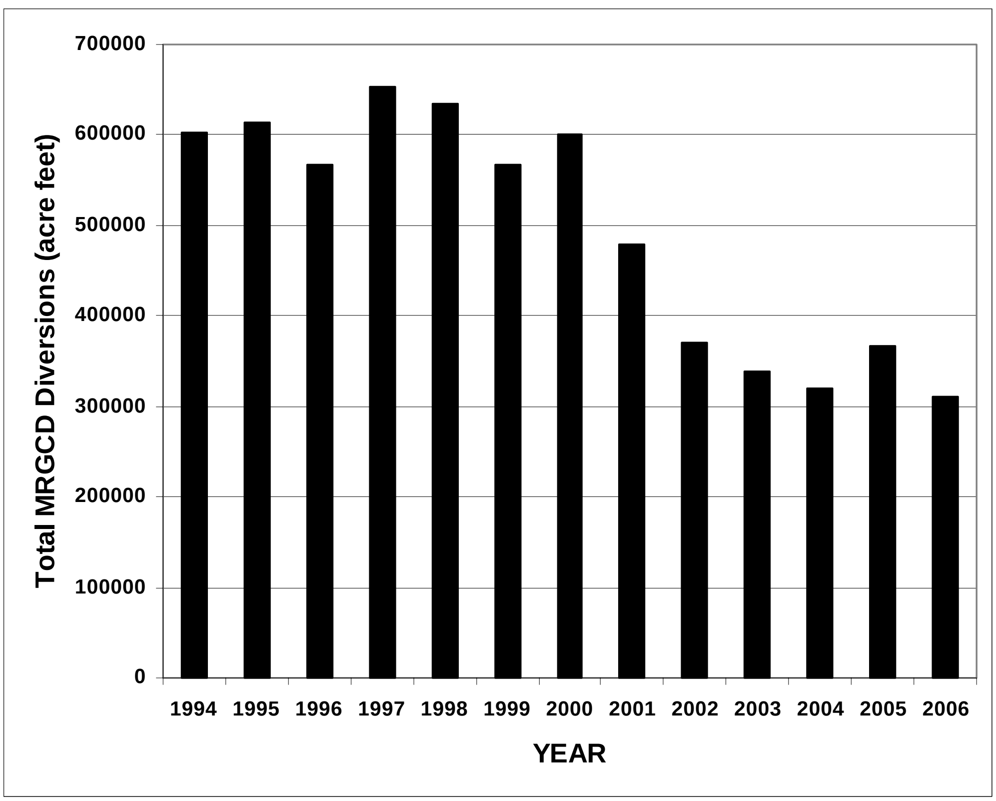


Figure 7. MRGCD River Diversions by Year

Implementation

The DSS will be implemented by being incorporated into the MRGCD Supervisory Control and Data Acquisition (SCADA) System. The DSS will give MRGCD operators a required irrigation delivery on a lateral level based on crop demand, as well as the timing of that irrigation. The required delivery and timing will be imported into the graphical user interface (GUI) of the MRGCD SCADA system so that actual deliveries along the canal system can be compared to the required deliveries. The GUI will allow water managers to remotely change automated gate settings so that actual diversions closely represent water requirements. This will provide better water management within the MRGCD and allow for a minimized river diversion as the required and actual diversion values converge.

CONCLUSIONS AND FURTHER RESEARCH

A decision support system for the Middle Rio Grande Conservancy District has been developed that models the canal network and can compute water delivery options for optimum water use. Using three modules, the model represents water demands, the irrigation network, and water scheduling aspects of irrigation. The model is fully capable of developing schedules for water delivery in the MRGCD and evaluation has shown that model recommendations are realistic and adequately represent ditch-rider practice.

Future work on the DSS will entail an in depth field investigation of model adequacy using soil moisture sensors and eventually the full implementation of the model. Model adequacy will be tested by closely monitoring fluctuations in RAM during a period where the schedule from the model is used exclusively. By determining whether the model effectively manages the moisture in the root zone, revisions and improvements to the model can be made. Once the field investigations are complete, the finalized model can be implemented for scheduling water deliveries throughout the entire MRGCD. Implementation will focus on incorporating the DSS into the already existing MRGCD SCADA system. By implementing the DSS for scheduling the MRCGD will further reduce river diversions and can continue to sustain irrigated agriculture in the Middle Rio Grande Valley.

ACKNOWLEDGEMENTS

The authors would like to thank the ESA Collaborative Program in New Mexico, the New Mexico Interstate Stream Commission, the National Science Foundation, and the staff of the MRGCD for the assistance and the financial support to undertake this research.

REFERENCES

Barta, R. 2003. Improving Irrigation System Performance in the Middle Rio Grande Conservancy District. Masters Thesis. Department of Civil Engineering, Colorado State University. Fort Collins, Colorado

DuMars, C.T. and S.C. Nunn (eds.). 1993. Working Document: Middle Rio Grande Conservancy District Water Policies Plan. Middle Rio Grande Conservancy District. Albuquerque, New Mexico.

King, J.P., A.S. Bawazir, and T.W. Sammis. 2000. Evapotranspiration Crop Coefficients as a Function of Heat Units for Some Agricultural Crops in New Mexico. New Mexico Water Resources Research Institute. Technical Completion Report. Project No. 01-4-23955.

New Mexico Interstate Stream Commission (NMISC); 2006 (authors Ramchand Oad, Luis Garcia, Dave Patterson and Kristoph-Dietrich Kinzli of Colorado State University, and Deborah Hathaway, Dagmar Llewellyn and Rick Young of S. S. Papadopulos & Assoc.); *Water Management Decision-Support System for Irrigation in the Middle Rio Grande Conservancy District*; March, 2006.

Oad, Ramchand and R. Kullman (2006). Managing Irrigated Agriculture for Better River Ecosystems—A Case study of the Middle Rio Grande. Journal of Irrigation and Drainage Engineering, Vol. 132, No. 6: 579-586. American Society of Civil Engineers, Reston, VA.

Rio Grande Compact Commission. 1997. Report of the Rio Grande Compact Commission, 1997

Shah, S.K. 2001. The Middle Rio Grande Conservancy District. Water, Watersheds, and Land use in New Mexico: Impacts of Population Growth on Natural Resources, New Mexico Bureau of Mines and Mineral Resources. Socorro, New Mexico. 123-125.

United States Fish and Wildlife Service (USFWS). 2003. Federal Register 50 CFR Part 17. Endangered and Threatened Wildlife and Plants; Designation of Critical Habitat for the Rio Grande Silvery Minnow; Final Rule. Vol. 68, No. 33. U.S. Department of Interior.

SALT MANAGEMENT: A KEY TO IRRIGATION SUSTAINABILITY IN ARID CLIMATES

J.D. Oster[1]
S.R. Kaffka[2]
D. Wichelns[3,4]

ABSTRACT

Salt management is a critical component of irrigated agriculture in arid regions. Successful crop production cannot be sustained without maintaining an acceptable level of salinity in the root zone. This requires drainage and a location to dispose drainage water, particularly, the salts it contains, which degrade the quality of receiving water bodies. Despite the need to generate drainage water to sustain productivity, many irrigation schemes have been designed and constructed with insufficient attention to drainage, to appropriate re-use or disposal of saline drainage water, and to salt disposal in general. To control the negative effects of drainage water disposal, state and federal agencies in several countries now are placing regulations on the discharge of saline drainage water into rivers. As a result, many farmers have implemented irrigation and crop management practices that reduce drainage volumes. Farmers and technical specialists also are examining water treatment schemes to remove salt or dispose of saline drainage water in evaporation basins or in underlying groundwater. We propose that the responsibility for salt management be combined with the irrigation rights of farmers. This approach will focus farmers' attention on salt management and motivate water delivery agencies and farmers to seek efficient methods for reducing the amount of salt needing disposal and to determine methods of disposing salt in ways that are environmentally acceptable.

Keywords: Drainage, Economics, Policy, Salinity, Salt Loads

IRRIGATE NOW – MANAGE SALTS LATER

Irrigation development and planning have become more sophisticated over time. Initially, irrigation developed opportunistically, initiated by individuals and small communities. Commonly, there was minimal planning, except for choosing the route of an irrigation canal, considering how to extract water from rivers, or determining where to drill irrigation wells. In some regions, this remains the extent of planning for irrigation schemes. Where government involvement with irrigation has increased, the planning effort expanded to include technical and economic feasibility analyses of projects involving public expenditures. Other important issues, such as the potential environmental impacts of irrigation, the opportunity costs of limited water resources, and the notion of sustainability have not yet been considered. In some areas where rivers were diverted to provide irrigation water, planners implicitly assumed that these rivers had the assimilative capacity to convey saline return flows to the sea.

---

[1]J.D. Oster, Univ. of California, 5192 Kendall, Riverside, California. james.oster@ucr.edu
[2]S.R. Kaffka, Dept. of Plant Sciences, Univ. of California, Davis, Calif. 95616. srkaffka@ucdavis.edu
[3]D. Wichelns, Dept. of Economics, Hanover College, Hanover, Indiana 47243. wichelns@hanover.edu
[4]All authors have contributed equally to the preparation of this paper

Planners are concerned primarily with designing adequate infrastructure to provide timely delivery of water supplies, while farmers are concerned with obtaining sufficient water to meet crop water needs, including water for leaching to maintain acceptable levels of salinity in the root zone. Planners have adjusted agricultural water rights to include the water lost to evaporation and crop transpiration, and the additional water required for leaching. Leaching requirements also generated the need to install subsurface drainage systems to control water table depths and prevent the loss of land due to secondary salinization, particularly on low-lying lands in arid regions. In many areas, however, drainage systems are not installed in a timely manner. In California's San Joaquin Valley, for example, the need for on-farm subsurface drainage systems and regional collector systems has long been recognized. Some systems have been installed and others planned, but much of the needed construction has been delayed and shallow water tables have developed. The need for drainage has become critical in those areas.

Only in recent years have planners and others begun appreciating environmental impacts and noting the importance of managing salts in irrigation return flows (van Schilfgaarde, 1994; Murray-Darling Basin Commission, 2001). Beginning in the 1970s, researchers sought ways to reduce the negative environmental impacts of irrigation and drainage in both small (van Schilfgaarde *et al*., 1974; Rhoades, *et al*., 1974; Oster and Rhoades, 1975) and field scale projects (Hoffman, et al., 1984; Rhoades *et al.*, 1988). They provided information that supported the concepts of increased application efficiency, minimum leaching, and salt storage within the soil profile (Rhoades and Suarez, 1977; Hanson and Ayars, 2002). Some of the concepts that were proposed and tested include: 1) serial biological concentration, in which the volume of water containing salt is reduced as much as possible (Rhoades, *et al*., 1988; Cervinka, *et al*., 1999, Kaffka, *et al*., 2002), 2) salt disposal on dedicated portions of irrigation schemes (Quinn *et al*., 1998; Murray-Darling Basin Commission, 2001), and 3) modified drainage system management to enhance crop use of shallow, saline groundwater (Ayars *et al*., 2006) thereby reducing drainage volume. The goals were to identify and demonstrate management strategies that increased the proportion of applied water used by crops, with consequent reductions in drainage water volume and salt loads.

The lack of focus on salt management and delays in constructing adequate drainage systems have contributed to substantial problems of salinity and waterlogging in many irrigated areas (Wichelns and Oster, 2006; National Research Council, 1989). In regions with poor natural drainage conditions, shallow water tables develop, soils become saline, and crop yields are reduced (Hillel and Vlek, 2005; Bouwer, 2000). Declining productivity reduces farm-level income, leaving farmers less able to pay for a drainage project that should have been installed initially. The regional salinity problem becomes more severe as farmers continue irrigating, while public discussion regarding the potential costs and benefits of constructing a regional drainage system continues.

Awareness of the inadequacy of the "irrigate now, manage salts later" approach has increased in recent years, due partly to the rising cost of building and operating irrigation schemes and the environmental impacts of saline drainage water. Public agencies responsible for water quality understand that salts in the drainage waters generated by irrigation often do not leave the region without impact. Rather, salts tend to accumulate in groundwater through deep percolation or they enter surface streams and lakes via surface runoff or from tile drain discharge. In either case, the increasing salinity of surface water and groundwater negatively impact water users located downstream, or those who rely on groundwater now and in the future for municipal or agricultural uses.

Public agencies generally have mandates to protect water quality for current and future generations and are becoming more involved in regulating the potential salinity impacts of irrigation in arid areas, such as in the San Joaquin Valley in California (National Research Council, 1989; Schoups, et al., 2005), the Colorado River Basin (van Schilfgaarde, 1982), and the Murray-Darling River Basin in Australia (Murray-Darling Basin Commission, 2001). Salt management is too expensive to ignore. Not only can environmental costs develop over time while irrigation is taking place, but the cost of retrofitting an irrigation scheme to control or mitigate environmental harm can become very large. In some areas the cost of collecting subsurface drainage water and removing salts and other constituents before discharging the water into rivers and other water bodies can reach levels that exceed the benefits of irrigation (Wichelns and Oster, 2006).

New policies and investments are needed to change the ways farmers irrigate and drain their fields, and dispose or re-use their drainage water. Both the costs and benefits of irrigation must be estimated when devising these policies. Ultimately the decision regarding the portion of the full costs of salt management paid by farmers will be determined through the political process. Planners and other analysts need to estimate the full costs accurately and impartially, and report their estimates in terms that can be understood readily by public officials, farmers, and other interested parties.

WATER RIGHTS AND SALT RESPONSIBILITIES

In the western United States, water is allocated according to a legal system of water rights that are clearly specified, enforced by the state, and sometimes tradable. Water rights are assigned to individuals and districts. Some states require that farmers and others use water in ways that are “reasonable,” such as irrigating crops and providing water for livestock. Unreasonable use of water can result in the loss of a water right. The concept of reasonable use allows for some degree of water quality degradation, given that return flows generally are of lower quality than water diverted for irrigation and other uses. However, the discharge of saline drainage water into receiving waters is constrained in some regions by efforts to achieve ambient water quality standards and protect water quality for downstream users.

In many arid areas, the responsibility for salt management is not yet defined or assigned as clearly as are rights to divert and use water in agriculture. At present, salts are managed by a combination of efforts by water delivery agencies, irrigation and drainage districts, and farmers. In the absence of clear responsibilities, many irrigators allow saline drainage water to flow into receiving surface waters or percolate into deep groundwater, while others dispose drainage water in evaporation ponds. Many farmers also re-use drainage water to augment irrigation deliveries or to comply with restrictions on drainage water disposal.

We think that it would be helpful to assign the responsibility for salt management to regional associations of farmers, as a condition of their right to use water for irrigation. This would: 1) enhance awareness of the salt management issue among irrigators, and 2) motivate water delivery agencies and farmers to seek efficient methods for reducing the amount of salt needing disposal and disposing salt in ways that are environmentally acceptable.

Farmers have several options to consider when given the responsibility for salt management. They might direct salt to an on-farm evaporation pond, or join with other farmers in forming a regional drainage district that coordinates salt collection and disposal efforts. Alternatively, farmers might hire contractors who agree to collect and dispose salts in a fee for services agreement. In the absence of surface disposal opportunities, which can occur where the depth to the water table is too deep to intercept drainage water with tile drainage, farmers or local drainage districts could optimize groundwater use to provide regional drainage (Fogg, 1999), allowing groundwater gradually to become more saline. Deep water tables can occur because the irrigated fields are located at the highest elevations of the irrigation scheme, or because groundwater pumping lowers the water table.

The regional aspects of drainage systems – tile drainage, use of groundwater for irrigation, or the combination of the two – would benefit from a coordinated regional program to optimize its duration. The program could include the re-use of moderately saline groundwater and tile drainage water for irrigation of salt tolerant crops (Kaffka et al., 2002; Cervinka et al., 1999). A local drainage district or regional drainage agency could develop and administer the program. A regional agency could build and operate a regional collector system to collect saline drainage water from many farms, with the goal of discharging the water into an evaporation pond, a nearby waterway or inland lake, or the ocean. The plan could also include financial incentives for farmers willing to re-use drainage water for irrigation. Under some circumstances, separating salt from drainage water using reverse osmosis or exchange membranes might be appropriate, although the costs of these options are substantial, and always involve disposal of saline brines in an environmentally acceptable manner.

EXAMPLES OF CURRENT SALT MANAGEMENT EFFORTS

The salinity management strategy for 2001 to 2015 in the Murray-Darling River Basin in southeastern Australia is a continuation of a regional, or watershed, planning process that began in the 1980s (Murray Darling Basin Commission, 2001). The strategy includes land management options to reduce salt loads to the river that originate from both dryland and irrigated agriculture. Engineering options include re-use of low salinity drainage water, conversion of open channels to piped water supplies to reduce seepage, salt interception and disposal schemes to divert groundwater or drainage water to safe disposal sites, and use of relatively non-saline groundwater for irrigation. The goal of maintaining an EC of 0.8 dS/m at least 85% of the time at Morgan, South Australia, located in the lower reach of the Murray River, was nearly achieved in 1999. However, salt stored previously in soils upstream of Morgan complicated efforts to achieve the 85% objective.

The Murray-Darling salinity management strategy recognizes possible impacts on the reliability of water supplies for irrigation. The need for maintaining flows that originate from relatively small areas that receive more than 800 mm of average annual rainfall is recognized, because those flows are particularly important to managing salinity levels in the river. The Murray Darling Basin Commission (2001) addressed this concern as follows:

> “Water supplies and management throughout the Basin have focused historically on ensuring reliable supplies for irrigation, mainly because of the undisputed benefits to regional economics and the Basin as a whole. It is becoming apparent, however, that increased priority must be given to maintaining flows from high rainfall areas and providing for more dilution and environmental flows. Unless this more balanced approach prevails, urban and other water users will have less water of poorer quality, and entire riverine ecosystems will be threatened. Further clarification of water property rights will be helpful in achieving a more balanced approach.”

In South Africa the current thinking is to develop watershed management plans (Du Plessis, private communication, 2007). Stakeholders within a watershed would assess the current state of the river and agree on its desired ecological state. They might choose to restore a natural river or maintain an impacted, regulated river. The next step would involve establishing quantity and quality objectives for the river, as the basis for developing a watershed management strategy. Sources of water quality degradation would be determined and remediation costs estimated. For existing systems, salt loads generated along different portions of rivers would be measured or estimated and management plans developed accordingly. For new irrigation developments, predictions of salt loading would be needed, based on the soils and geology of the irrigated region.

The European Commission’s Water Framework Directive (WFD), passed in 2000, pertains primarily to water quality issues (Playan, private communication, 2007). The Directive requires that all waterbodies in Europe attain "good ecological status" by 2015, a goal that could have notable implications for salinity control of rivers in Europe, although salinity is not mentioned in the Directive (http://ec.europa.eu/environment/water/water-framework/overview.html) because it is not generally an issue in the EU region. The WFD was reinforced in 2003 and a groundwater directive was added. Many of Europe’s aquifers are impacted by pollution from several sources, including nitrogen applications in agriculture.

The assessment of environmental impacts in Europe will require regional coordination. According to the WFD, the price of water for all uses must reflect: 1) the cost of making water available, 2) water scarcity, and 3) the cost of cleaning up all water pollution generated by the user. The WFD approach suggests that water and salt management will be conducted in parallel in semiarid regions. The cost of the program might have substantial impacts on farm-level crop choices. Several Mediterranean governments are implementing agricultural aspects of the WFD somewhat slowly, due to concerns regarding the potential financial impacts on the sector. However, river basin authorities in these areas are giving greater attention to salinity control and management (Playan, private communication, 2007)

AN IRRIGATION AND DRAINAGE PROSPECTIVE

The world has obtained great benefits from irrigated agriculture for thousands of years, both in arid and humid regions. Some might suggest there is little need for proposing a substantive change in the way that irrigation schemes are planned and policies are chosen. We argue that a new approach is needed, particularly in arid regions. The fundamental issues regarding salts and drainage necessary to sustain irrigated agriculture are well known. The environmental impacts are becoming better understood, and the costs of salt disposal are substantial.

Planning for salt management is more complicated than planning for water management. Irrigation water is not the only source of salt in drainage water in arid climates – native salts are present in the soil. The salt content of drainage water varies with how it is collected – the depth and spacing of the tile system (Ayars, 1999), the management of the drainage system (Ayars, 2006) and the depth and spacing of groundwater wells (Quinn, 1991). The salt load in drainage water changes with time as the soil adjusts to the chemical composition of the irrigation water. The amount of drainage water, and to some extent its salt load, varies with irrigation efficiency, the fraction of applied water that is used by the crop. Re-use of drainage water for irrigation reduces the volume requiring management and disposal, but some re-use practices can complicate farm-level efforts to maintain soil salinity within an acceptable range.
Regional efforts to maintain ambient water quality standards in receiving waters will require continual monitoring of drainage water volumes and salt loads by staff members of public agencies. Their efforts, and the associated public costs of maintaining water quality standards, can be reduced by assigning responsibility for salt management to farmers as a condition of their water rights.

Implementing and enforcing responsibility for salt is not easy (Murray Darling Basin Commission, 2001). Compared with relying on regulation, an incentive-based approach can accomplish the same goal at a smaller aggregate cost. Farmers will be motivated to seek methods for reducing the amount of salt needing disposal and determining low-cost methods for disposing salt in an environmentally acceptable manner. A purely regulatory approach will not provide the same motivation to develop less costly disposal technology.

Some observers will suggest that agriculture requires special consideration when discussing environmental goals because farmers use a large volume of water to produce crops of relatively low market value. They may be subject to competition with farmers in other regions where the costs and burdens of salt disposal are ignored. If the “polluter pays” principle is applied to agriculture, irrigation might become non-viable in some areas, and new irrigation schemes might not be developed. This result is particularly likely in arid and semiarid areas where native soils are saline. If society needs the food and fiber produced by irrigated agriculture in such regions, policy makers might need to consider accepting lower water quality standards. Alternatively they might decide to provide financial support of water and salt management practices that minimize environmental impacts. Such considerations will be based on the perceptions of policy makers regarding the present and future benefits irrigation provides, the public value of achieving irrigation sustainability in arid regions, and the public’s interest in protecting water quality.

The problems with salt management along the Murray-Darling Basin (Murray Darling Basin Commission, 2001), the Colorado River Basin, and along the west side of the San Joaquin Valley (Wichelns and Oster, 2006) attest to the need to improve planning for salt management. Perhaps there are two approaches the agricultural community might take regarding salt management in the future: 1) Allow policy makers to work through a regulatory process that will mandate changes needed in irrigated agriculture to achieve water quality objectives – a non-engaged approach, or 2) Implement programs that encourage farmers to develop options to optimize both water and salt management, and to propose them to policy makers – a proactive approach. Optimal solutions likely will emerge if policy makers, planners, farmers, and other stakeholders take the opportunity to be part of the planning process.

REFERENCES

Ayars, J.E., Christen, E.W., Hornbuckle, J.W., 2006. Controlled drainage for improved water management in arid regions irrigated agriculture, *Agricultural Water Management*, 86(1-2):128-139.

Ayars, J.E., 1999. Managing irrigation and drainage systems in arid areas in the presence of shallow groundwater: case studies. *Irrigation and Drainage Systems* 10(3): 227 - 244.

Bouwer, H., 2000. Integrated water management: emerging issues and challenges. *Agricultural Water Management* 45(3):217-228.

Cervinka, V., Diener, J., Erickson, J., Finch, C., Martin, M., Menezes, F., Peters, D., Shelton, F., 1999. Integrated system for agricultural drainage water management on irrigated farmland. Final Research Report, 4-FG-20-11920. Bureau of Reclamation, U.S. Dept. of Interior, Washington, D.C., 41 pp.

Fogg, G., 1999. Groundwater management. Groundwater Management Technical Committee. The San Joaquin Valley Drainage Implementation Program and the University of California Salinity/Drainage Program. Department of Water Resources. Sacramento, California.

Hanson, B.R., Ayars, J.E., 2002. Strategies for reducing subsurface drainage in irrigated agriculture through improved irrigation. *Irrigation and Drainage Systems* 16:261-277.

Hillel, D., Vlek, P., 2005. The sustainability of irrigation. *Advances in Agronomy* 87:55-84.

Hoffman, G.J., Oster, J.D., Maas, E.V., Rhoades, J.D. Van Schilfgaarde, J., 1984. Minimizing salt in drain water by irrigation management - Arizona field studies with citrus. *Agricultural Water Management* 9:61-78.

Kaffka, S.R., Oster, J.D., Corwin, D.L., 2002. Using forages and livestock to manage drainage water in the San Joaquin Valley. Symposium no. 34:2059-1 to 2059-12. In: Kheoruenrome, I. (Ed.), 17th World Congress of Soil Science. August 14-21, 2002. Bangkok, Thailand.

Murray-Darling Basin Commission. 2001. Basin Salinity Management Strategy 2001 – 2015 (www.mdbc.gov.au. Accession date: February 2007).

National Research Council. 1989. Irrigation-induced water quality problems: what can be learned from the San Joaquin Valley Experience. National Academy Press, Washington D.C., 157 pages.

Oster, J.D., Rhoades, J.D., 1975. Calculated drainage water compositions and salt burdens resulting from irrigation with river waters in the western United States. Journal of Environmental Quality 4:73-78.

Quinn, N.W.T., 1991. Groundwater pumping for water table management and drainage control in the Western San Joaquin Valley, pp71-97. In: Dinar, A., Zilberman, D. (Eds.). The Economics of Water and Drainage in Agriculture. Kluwer Academic, Dordrecht, The Netherlands.

Quinn, N.W.T., McGahan, J.C., Delamore, M.L., 1998. Innovative strategies reduce selenium in Grasslands drainage. California Agriculture 52(5):12-18.

Rhoades, J.D., Suarez, D.L., 1977. Reducing water quality degradation through minimized leaching management. *Agricultural Water Management* 1(2):127-142.

Rhoades, J.D., Oster, J.D., Ingvalson, R.D., Tucker, J.M., Clark, J., 1974. Minimizing the salt burdens of irrigation drainage waters. Journal of Environmental Quality. 3:311-316.

Rhoades, J.D., Bingham, F.T., Letey, J., Pinter Jr., P.J., LeMert, R.D., Alves, W.J., Hoffman, G.J., Replogle, J.A., Swain, R.V., Pacheco, P.G. 1988. Reuse of drainage water for irrigation: results of Imperial Valley Study. II. Soil salinity and water balance. Hilgardia 56(5):17-44.

Schoups, G., J.W. Hopmans, C.A. Young, J.A. Vrugt, W.W. Wallender, K.K. Tanji, and S. Panday, 2005. Sustainability of irrigated agriculture in the San Joaquin Valley, California. *Proceedings. of the National Academy of Sciences* 102(43):15352-15356.

van Schilfgaarde, J., Berntstein, L., Rhoades, J D., Rawlins, S.L., 1974. Irrigation management for salt control. Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers. 100, No. IR3: 321 -

van Schilfgaarde, J., 1982. The Wellton-Mohawk Dilemma. *Water Supply & Management* 6(1/2):115-127.

van Schilfgaarde, J., 1994. Irrigation – a blessing or a curse. *Agricultural Water Management* 25(3):203-219.

Wichelns, D., Oster, J.D., 2006. “Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial,” *Agricultural Water Management* 86(1-2):114-127.

GHAZI BAROTHA PROJECT ON INDUS RIVER IN PAKISTAN

Engr. Dr. Illahi. B. Shaikh[1]

ABSTRACT

In order to use the available water from the Indus River and use the natural head of 76 meters available in the area, the Government of Pakistan has constructed the Ghazi Barotha Project on the Indus River through the Water and Power Development Authority (WAPDA), which also produces 1450 MW of hydropower. The project is running successfully with minimal environmental disruptions and has properly addressed resettlement issues in consultation with donors. This paper describes the Ghazi Barotha Project in Pakistan.

BACKGROUND INFORMATION

Only about 3 % of the world's total water resource is fresh (non-saline) water, of which roughly one-third is inaccessible. The rest is unevenly distributed. In many areas, the existing water resources are increasingly contaminated with wastes and pollution from industrial, agricultural and domestic sources. Over the years, rising population, growing industrialization, and expanding agriculture have led to a rising demand for water. South Asia is one of the most densely populated regions of the world. It houses roughly one-fifth of the world's population, and this share is likely to increase to one-fourth of the total world population by the year 2025. The economies of the countries in the region are heavily dependent on agriculture.

In the case of Pakistan, water has played a very significant role in the nation's economic development and will continue to be a driving force in its future development. Agriculture is the largest sector of the economy, with primary commodities accounting for 25% of Pakistan's GDP and 47% of total employment, and contributes more than 60% of foreign exchange earnings. The principal crops include wheat, rice, cotton, sugarcane, oilseeds, fruits, vegetables, pulses. The overall yield per hectare of most crops is far below their demonstrated potential. Irrigated agriculture yields can be increased through use of improved technology and better management of the highly complex agricultural management system.

Pakistan, with a geographical area of 796,101 square kilometers, contains the large Indus River which, alongwith its 5 tributaries (Chenab, Jhelum, Ravi, Kabul and Sutlej), forms one of the mightiest river system of the world. The irrigation system currently serves an area of 17 million hectares (42 million acres). The Indus River and its western tributaries bring an average of about 175 BCM (142 MAF) of water annually and the average annual canal withdrawal is 128 BCM (104 MAF).

The Indus River System is comprised of :

---

[1] Chief Engineering Adviser/ Chairman, Federal Flood Commission; Ministry of Water and Power; Chairman, Pakistan National Committee of ICID. pakfloodcommission@hotmail.com

- 19 large river headworks
- 45 independent irrigation canal systems measuring 64,000 kilometers.
- Approx. 1.6 million kilometers of water courses
- 94 large dams with heights of 15 meters and above, including 3 super storage reservoirs.
-

Figures 1 and 2 show a map and schematic diagram of the Indus River Irrigation System.

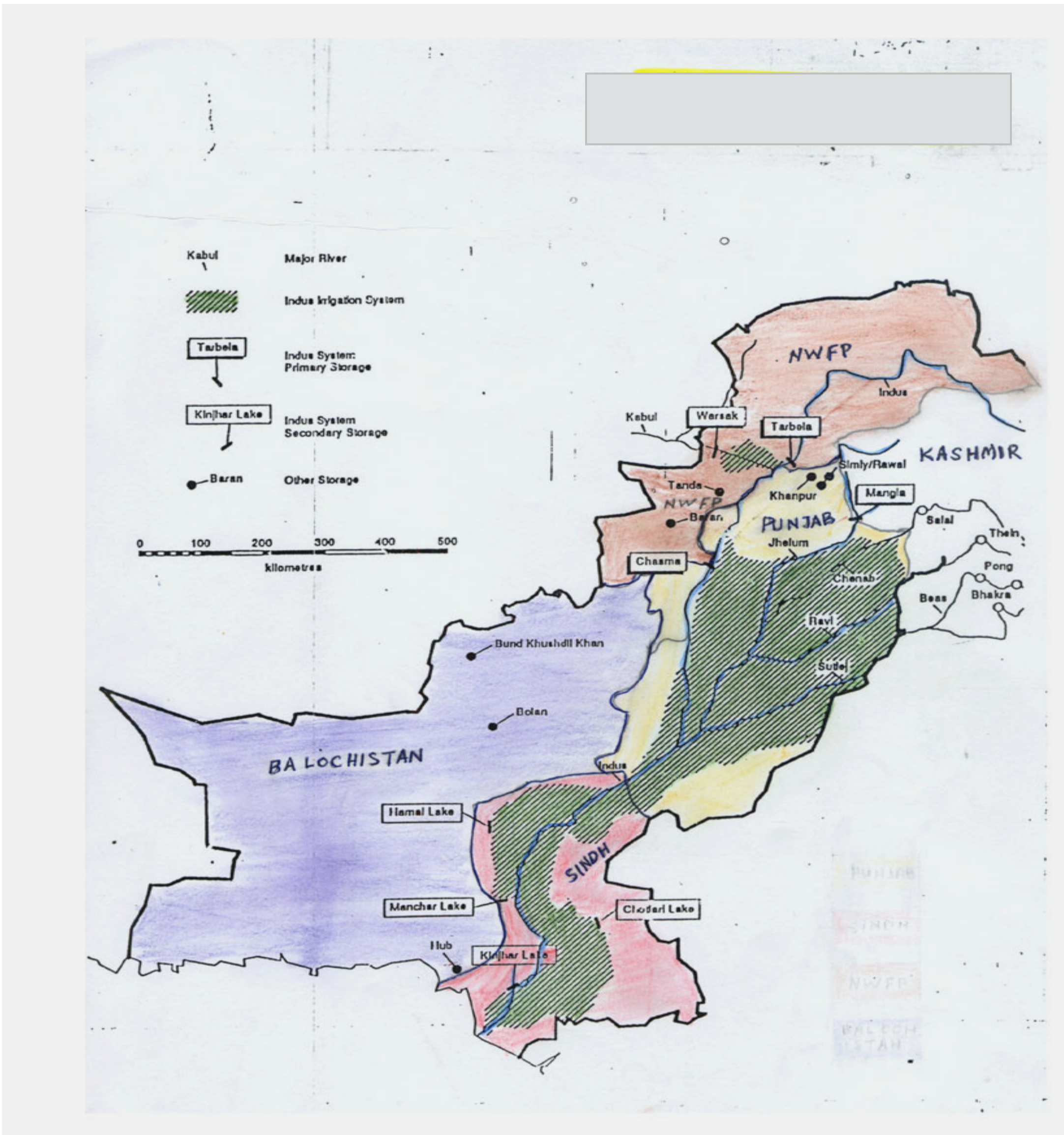


Figure 1. Indus irrigation system and surface storage map

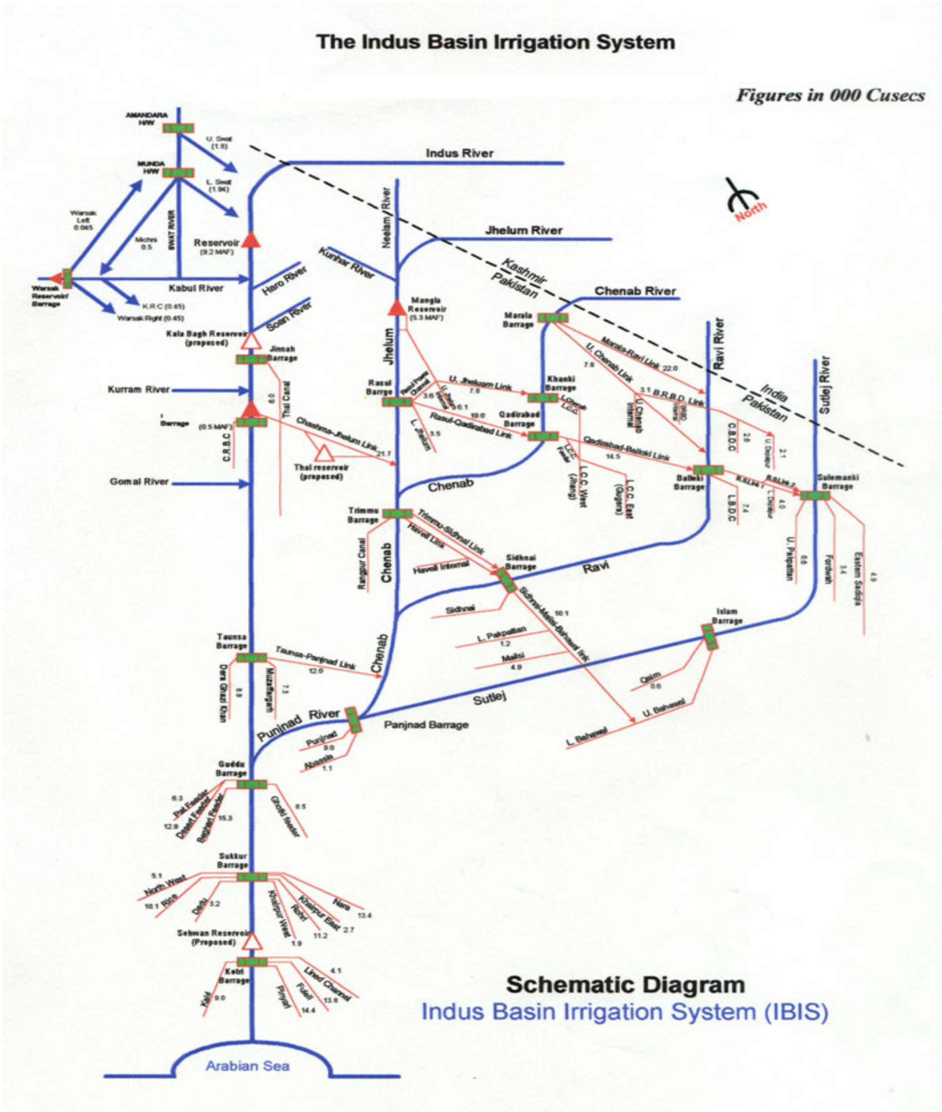


Figure 2. Indus Basin irrigation system diagram

Pakistan is a country of over 150 million people, which is expected to grow to about 221 million by the year 2025. The most pressing need over the next quarter century in Pakistan will be the management of the rapidly increasing population and provision of basic amenities. The increasing population will have a major impact on food and fiber requirements.

As the population continues to grow, Pakistan is now essentially at the limit of its water resources and is becoming a water scarce country. There is a strong and growing need to manage this precious resource more carefully and efficiently to ensure water for all on a sustainable basis. In order to effectively use water to meet the future demands for food and rural development, there is need to evolve strategies for development, management and conservation of water resources. A good proportion of the water which will supply the additional needs of the future must come from conservation and continued investment in the Irrigation, Drainage and Hydropower Sector. The food needs of the future can only be met through combined efforts in water conservation, additional storages and most importantly through increases in crop yields.

Additionally, Pakistan's large river systems have discharges during the summer season that can vary from 3,000 to 34,000 Cusecs (100, 000 to 1,200,000 Cumecs) and which cause tremendous losses to human lives, crops and property. Due to the limited storage capacity at the Tarbela and Mangla Dams (on the Indus and Jhelum rivers, respectively) and with virtually no control on the Chenab, Ravi and Sutlej rivers, devastating problems occur between July and October in the event of excessive rainfall in the catchments.

GHAZI BAROTHA

The town of Ghazi in Tehsil Haripur is just 7 kilometers downstream from Tarbela Dam. The Project Layout plan and a photo of the barrage are shown in Figures 3 and 4. Between Ghazi and Barotha, the Indus River drops 76 meters. WAPDA decided to build a structure to divert water into a 51,900 meter power channel that follows a relatively flat gradient as compared to the river, providing a drop of 69 meters. After producing electricity, the water is returned back to the Indus River. WAPDA carried out initial feasibility studies in 1987. In 1991, feasibility studies were completed by Pakistan Hydro Consultants, a joint venture of NESPAK (the largest engineering national consulting firm) and ACE from Pakistan, Ewbank and Binnies from the United Kingdom, and Harza from the United States. Pakistan Hydro Consultants also acted as WAPDA's consultant for design and construction supervision during the development of Ghazi Barotha.

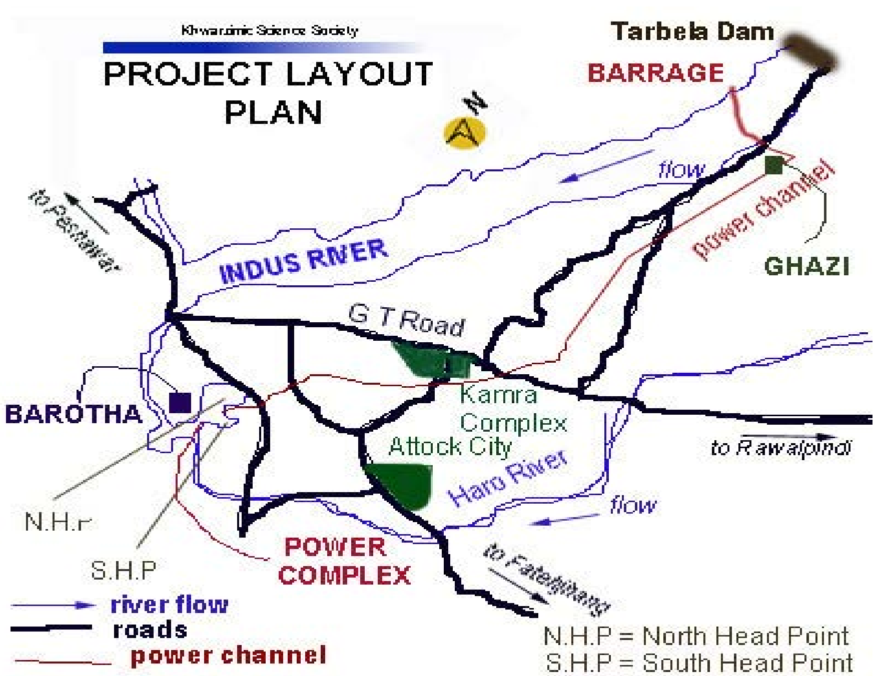


Figure 3. Project Layout

Figure 4. Ghazi Barotha Barrage on the Indus River in Pakistan

Quantities of indigenous oil, gas or fossil fuels in Pakistan are limited, so the focus of energy proposals are currently on hydropower to minimize the fuel import burden. The Water and Power Development Authority (WAPDA) designed the 1,450 MW Ghazi Barotha Project on the Indus River to fulfill this vital need. Unlike WAPDA's 1,000 MW Mangla Dam on the Jhelum River and 3,478 MW Tarbela Dam on the Indus, Ghazi Barotha is not an impoundment dam but a run-of-the- river project. Ghazi Barotha provides examples of several "good practices" in hydro development. In spite of various implementation difficulties related to site conditions and funding shortfalls, WAPDA completed the project with only a 7.96 % increase in the original estimated cost. The completion cost of the project was Rs 96,957 million and the project was fully completed on June 30, 2006 with EIRR as 22.19%. Of note is the unique design of the water channels and powerhouse, which allowed WAPDA to minimize environmental and social effects. Today, Ghazi Barotha contributes 6,600 gigawatt-hours (GWH) of environmentally-friendly electricity to more than 2 million homes each year.

UNIT COST ANALYSIS

i)	Installed Energy		=	1450 MW
ii)	Average units generated		=	6586 GWh
iii)	System losses and consumption in auxiliaries		=	1589.64 GWh
iv)	Net units available for sale		=	5005.36 GWh
v)	Annual recurring charges		=	Rs 8500 M
vi)	Cost per unit generated	= (8500/6586)	=	Rs 1.29 = 0.021 US$
vii)	Cost per unit sold	= (8500/5005.36)	=	Rs 1.70 = 0.028 US$

CONCLUSION

As the population grows there is strong and growing need for Pakistan to manage its precious water and other energy resources more carefully and efficiently and sustain continued investment in Irrigation, Drainage and Hydropower Sectors to meet the future demands of food and energy.

REFERENCES

Shaikh I. B (2005) Research Thesis on Water Resources Management of Pakistan and Analysis for Future Strategy – Pakistan

Pakistan Water & Power Development Authority (WAPDA) PC-IV Project Completion Report 35 P.

Shaikh I. B & Engr. Qazi Tallat Mahmood Siddique (2007) Paper on “Water Resources Management Technologies for Barani Areas of Pakistan”

FIELD TESTS OF OSIRI — A DECISION-MAKING TOOL FOR IRRIGATION OF SUGARCANE FARMS IN REUNION

J.-L.Chopart[1] F. Aure[2]
L. Le Mézo[1] M. Mézino[1]
J. Antoir [2] M.Vauclin[3]

ABSTRACT

A decision-making software tool for monitoring irrigation of small farms in heterogeneous environments (OSIRI) was developed at the request of small-scale sugarcane farmers on the island of Réunion (France) hampered by variable climate and soil conditions. This program, which is based on a simple water balance simulation model coupled with a comprehensive set of decision rules, was designed to provide farmers with customized advice on discrete irrigation units and to simulate irrigation system scenarios so as to optimize their performance. The basic equations and main decision rules of OSIRI, as well as the software features, were given in Chopart et al. (2007). A detailed experimental study was carried out on a 5000 m^2 irrigated sugarcane field to compare the performance of this tool with the currently used method based on maximum crop water requirements (control). The results showed that OSIRI reasonably well simulates actual evapotranspiration and drainage below the sugarcane root zone. Moreover, it allowed savings of about 26% in irrigation delivery throughout the crop cycle as compared with the control method, without a significant decrease in yield, and irrigation water productivity increased by 25%. The results of a survey of 25 farmers using OSIRI showed that it is a well accepted valuable decision-making tool.

INTRODUCTION

More water is applied than necessary in many irrigated systems, particularly when water fees are low. In Réunion, with a growing population and urbanization, industrial and domestic water use is rising, thus boosting competition with the agricultural sector for this resource. Public and regulatory agencies are now concerned about the possible contamination of water bodies due to the increasing use of agrochemicals and the development of newly irrigated areas on the island (eg Bernard et al., 2005). Consequently, agricultural water resource management should be optimized to maintain a sustainable usage level, particularly by developing irrigation-monitoring tools adapted to local environmental and socioeconomic conditions, such as high climate and soil variability at small scales, tiny fields and poorly trained farmers. Although several such tools are available, most were specifically designed for surface irrigation (eg Rowshon et al., 2003a and 2003b, Georges et al., 2004). Tools for sprinkler irrigation (eg Cabelguenne et al., 1996, Dechmi et al., 2003a and 2003b, Stirzaker and Hutchinson, 2005) and drip irrigation (eg Wieldenfeld, 2004) require equipment and

[1] CIRAD, 7 chemin de l’Irat Ligne Paradis 97410 Saint Pierre, La Réunion, France
[2] Chambre d’Agriculture de la Réunion, BP 134 97463 Saint Denis, La Réunion, France
[3] CNRS, LTHE-UMR 5564 (CNRS, INPG, IRD, UJF) BP 53 38041, Grenoble Cedex 9, France
Chopart J.-L., tel.: (+33) 262499262, fax: (+33) 262499295, email: chopart@cirad.fr
Aure F., tel.: (+33) 262248288, fax: (+33) 262248455, email: r.eau@reunion.chambagri.fr
Le Mézo L, tel.: (+33) 262499264, fax: (+33) 262499295, email: lemezo@cirad.fr
Mézino M., tel.: (+33) 262499263, fax: (+33) 262499295, email: mezino@cirad.fr
Antoir J., tel.: (+33) 262962066, fax: (+33) 262962070, email: eau.suad.@reunion.chambagri.fr
Vauclin M., tel.: (+33) 476825056, fax: (+33) 476825286, email: lthe@hmg.inpg.fr

input data that are not readily available to Réunion farmers. Recommendation tools for small-scale irrigation include: (i) water state indicators for plants like leaf temperature (Jackson et al., 1981) or soil (Ozier-Laffontaine and Cabidoche, 1995), (ii) soil water balance models (eg Smith, 1992; Imman-Bamber et al., 2002), and (iii) data sheets based on average climatic forcing and crop water requirements. The water state indicator-based approaches are not applicable to Réunion because the soil types are highly variable and *in-situ* measurements would be too cumbersome.

The Agricultural Extension Service (AES) of Réunion currently provides recommendations for irrigation based on crop water requirement estimates calculated according to regional mean potential evapotranspiration (ET_0) and crop coefficient values (Doorenbos and Pruitt, 1977). Hereafter, this method will be referred to as MET-rec. However, this approach was not satisfactory in many places. The new OSIRI tool was thus developed in collaboration with farmers and the AES so as to provide them with better operational advice (Chopart et al., 2007). After summarizing the main features of OSIRI, this paper presents the results of a 1-year evaluation of the tool against field data. They are also compared with results obtained by using the MET-rec method. Finally, the results of a survey conducted among a sample of 25 farmers who used OSIRI to assess its acceptability, usefulness and ease of use are given.

MATERIALS AND METHODS

The study was conducted in southern and western Réunion (21°S, 55°E, Figure 1a). Because of its compact orography (highest elevation: 3100 m), climatic variability is spatiotemporally high. Annual rainfall ranges from 0.5 to 10 m depending on the location along the coast and the elevation, with steep gradients on a kilometric scale. The main crop is sugarcane (26500 ha, year 2006), with at least half of the fields irrigated. Most irrigated farms are less than 5 ha. Each farmer gets water from an outlet at a constant flow rate. An irrigation unit may consist of subdivided field units. In sprinkler irrigation, farmers irrigate each unit sequentially. The time between two irrigations ranges from 2 to 10 days. Drip irrigation usually takes place once a day. The time interval between two irrigations is proportional to the time required to irrigate all units of a farm from the same water outlet. Irrigation systems are often monitored by a computerized irrigation autotimer. Farmers can seek advice from an AES officer but there are not enough officers to meet the needs.

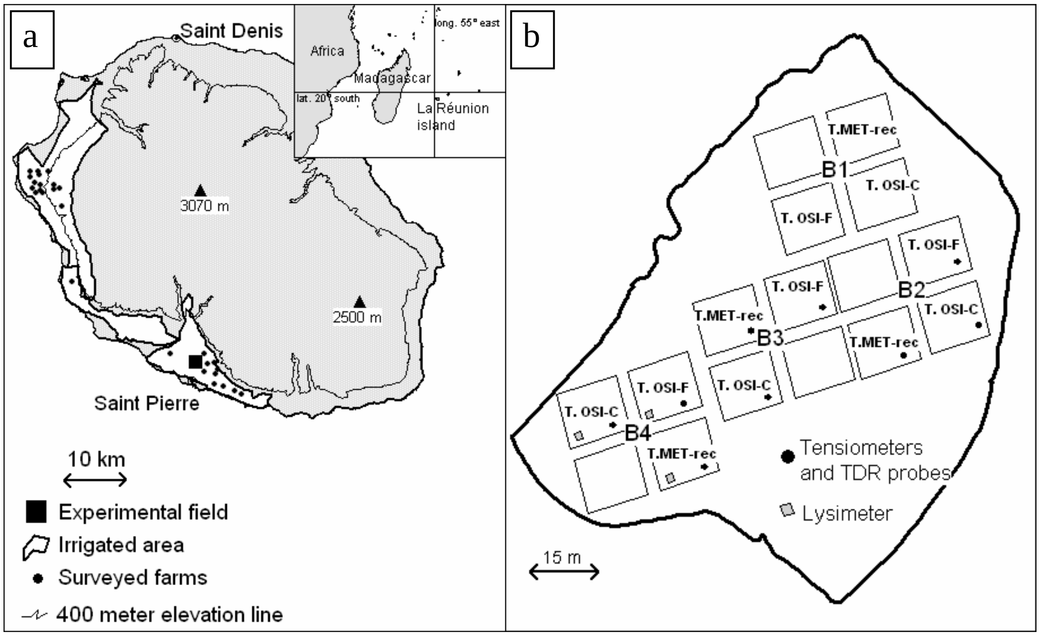


Figure 1. Map of the island of Réunion showing the locations of the surveyed farms (1a) and a schematic representation of the experimental setup (1b). The fourth plot of each block was cultivated with an irrigation deficit (data not reported)

OSIRI software description

The French acronym OSIRI stands for “Outil Simplifié pour une Irrigation Raisonnée et Individualisée” (i.e. simple decision–making tool for sustainable individual irrigation monitoring). This easy-to-use product is designed to optimize irrigation water and rainfall use, while taking irrigation parameter and environmental factor variations into account. The software can be operated on any Office 2000®-run PC through Windows (Microsoft®) on Excel 2000® spreadsheets (or more recent versions). Data are saved in Excel® files compatible with standard spreadsheets. English, French or Portuguese versions are available free of charge on request.

OSIRI was designed to provide irrigation recommendations for single sprinkler units or dripper lines or for large jointly irrigated areas. Whenever irrigation is possible, depending on the irrigation frequency, the amount of water to be delivered is calculated by algorithms with several factors taken into account: predicted rain, daily actual soil water storage rates estimated through the PROBE model (Chopart and Vauclin, 1990), crop water requirements, water delivery flow rates at the outlet, irrigation duration and frequency, as well as available soil water storage constraints (see below). Predicted rainfall is estimated on the basis of frequency analyses of rainfall recorded at the nearest meteorological stations. A daily simulation of the PROBE water balance is then carried out for the next water roster, with programmed irrigation and predicted daily rainfall.

This provides a forecast of the actual water storage level in order to determine the irrigation dose for the next water roster. These calculations are ongoing until harvest. This provides the farmer with an estimation of irrigation application needs for the whole cropping season, thus facilitating irrigation scheduling. For each irrigation-monitored unit, the recommended applications are presented in two ways: (i) per irrigation unit for the duration of the crop cycle, and (ii) per month for all units. It is advisable to periodically update the water balance calculation by considering actual rainfall and irrigation applications in order to adjust the soil water level and maximize the efficiency of the recommendations. This task is fulfilled by an extension officer, but the farmer may adjust the irrigation applications according to actual rainfall between two visits by the officer. One OSIRI module proposes a simple method for this operation. Five functions are listed on the OSIRI home page: (i) creation or cancellation of irrigation units, (ii) recording of rainfall or irrigation application data, (iii) calculation and editing of water balance and recommendations, (iv) printing and export of data and recommendations, and (v) exiting OSIRI. Only basic computer notions are required to use the software. More detailed information is available in Chopart et al. (2007) and in the user guide (Chopart et al., 2005).

The farmer, alone or with the assistance of an AES officer, starts by creating a new file containing all irrigation units sharing the same climate inputs. Once a first soil water balance simulation has been achieved, OSIRI suggests an irrigation schedule applied to each water roster until harvest. A recommendation preview allows the user to check whether the whole process and first choices lead to irrigation applications in line with the farmer's initial requirements. If not, the strategy can be changed by modifying elements. Recommendation sheets are edited when the proposed irrigation calendar meets such requirements.
These guidelines enable farmers to program irrigations at the beginning of the recommendation period. They subsequently have to record water volumes used and rainfall levels during this given period. Then they have the alternative to make a new soil water balance calculation with actual irrigation applications and rainfall for another recommendation or to adjust the data by a simplified method.

Field test

Experimental setup and irrigation methods tested. The experimental setup consisted of four blocks within a 5000 m^2 field on a sugarcane farm in southern Réunion (Figure 1b). The soil is clayey, derived from recent volcanic rock (Cambisol). It is more than 2 m deep and has a dry bulk density close to 1 g/cm^3. The field had been cropped with sugarcane for several years before the experiment took place during the 2005-2006 crop season. It was irrigated with a fixed sprinkler system to obtain a uniform water supply. Three 160 m^2 plots were randomly located within each block. They were managed according to the following three irrigation advice tools: (i) T.MET-rec: irrigation was conducted as recommended by the monitoring sheet. If total rainfall during the 5 previous days exceeded 30 mm, then no irrigation was applied for 5 days (one water roster), (ii) T.OSI-F (F = farmer): irrigation was applied as recommended by OSIRI, and as routinely carried out by farmers, with soil water storage calculations updated once a month to adapt to the harsh local constraints experienced by farmers, and (iii) T.OSI-C (C = control): irrigation was conducted according to the OSIRI water roster advice (5 days). This was considered as the control treatment. Three blocks were equipped with TDR probes and tensiometers implemented between 0.2- and 2 m depths in order to estimate components of the soil water balance.

In addition, three single-block plots were equipped with free-drained lysimeters of 2.25 m^2 surface area and 180 cm depth. They were carefully filled with soil taken from the surrounding field and packed in such a manner that their properties were similar. The bottom was equipped with an automatic water outflow measuring device. Rainfall was automatically recorded as well. A sugarcane row was planted in each lysimeter in such a way that the plant density was the same as that of the surrounding field. The lysimeters were set up 2 years before the field study so as to obtain uniform soil and crop conditions.

Treatments were applied after 1 year of homogeneous sugarcane cultivation. In terms of irrigation monitoring, the following input parameters common to all three tools were: (i) climatic data (rainfall and potential evapotranspiration), (ii) water roster period (5 days), (iii) crop regrowth date (October 31, 2005) and harvest date (October 30, 2006), and (iv) crop coefficient time-course (Chopart et al. 2007). In addition, T.OSI-Ag and T.OSI-C require the following complementary input parameters: (i) irrigation efficiency (IE = 80%), (ii) maximum available soil water storage (0.072 cm of water per cm of soil), (iii) drainage depth (DZ = 180 cm), and (iv) root depth (RD = 120 cm). Note that RD was considered temporally constant since the field study addressed the sugarcane regrowth stage. Maximum filling of the root zone reservoir and the irrigation triggering threshold (see Chopart et al., 2007) were set at 80% and 60% of the maximum available water storage of the root zone (68 mm), respectively.

<u>Comparison between measured and OSIRI-calculated values</u>. T.MET-rec, T.OSI-F and T.OSI-C were compared with respect to three water balance components: (i) total irrigation delivery, (ii) drainage loss below the root zone (DT), and (iii) actual evapotranspiration (AET). They were also compared according to yields and irrigation water productivity, defined as the ratio between the millable yield and irrigation volume and calculated for the 12-month growing season.

The OSIRI software soil water balance component was run for both treatments (T.OSI-F and T.OSI-C) with its required soil and crop data. It was forced by actual rainfall and irrigation quantities. For the lysimeters, experimental AET values were obtained on the basis of the difference between water input (rainfall + irrigation) and drainage losses measured at baseline since the experimental conditions led to a quasi-steady-state water flow regime after the first stage of growing season (0-60 DAR). OSIRI recommendation tools were compared with field soil water storage variations (ΔS) measured by TDR probes. They just gave estimates of the sum of cumulative AET and drainage values between two dates. This calculation is useful when drainage is either nil or very low. Fortunately, the lysimeter measurements indicated low drainage, as confirmed by the tensiometer readings (data not reported) during four periods ranging from 20 to 36 days long. This enabled calculation of cumulated AET+ DT, which here resulted in water losses, from ΔS. Differences between measured and OSIRI-calculated values of AET and DT were analyzed according to the following classical statistical entities: Nash efficiency coefficient (NE), root mean square error (RMSE), and mean bias (MB). They should be as close as possible to 1, 0, and 0, respectively.

<u>Farm survey</u>

To evaluate the end user’s degree of satisfaction of OSIRI, a survey of 66 farmers who had been using the tool for more than 1 year, or who were beginning to use it during the current sugarcane cycle, was carried out. They were distributed in two regions more than 30 km apart (Figure 1). A sub-sample of 25 randomly selected farmers was considered for the analysis. The survey was conducted by a student who had not been involved in designing OSIRI, thus reducing the survey response bias. Farmers were asked about their irrigation practices before and after using the OSIRI advice tool. The main questions were: (i) What is your overall impression? (ii) Do you consider that water doses suggested by OSIRI are: too small, adequate, or too high? (iii) Has irrigation water consumption increased or decreased? and (iv) Is irrigation control easier or more difficult as compared to your previous situation? A score ranging from 1 to 5 was assigned to each answer (see below).

Additional information was collected to try to explain variations in different farmers' responses, such as: age, type of training, duration of experience in using OSIRI (first year or second year), type of irrigation advice used before OSIRI, irrigation programming mode (control programmed in terms of time or volume). Two types of training were identified: practical irrigation training without agricultural studies (I), and basic agricultural studies complemented by practical irrigation training (AI).

RESULTS

Experimental test

Comparison of irrigation applied according to OSIRI and MET recommendations. As Table 1 shows, no significant difference was noted between the two versions of OSIRI (T.OSI-F and T.OSI-C). Irrigation amounts programmed by the currently used T.MET tool were, however, higher than those recommended by OSIRI. For the whole 360 day period, OSIRI allowed irrigation savings of about 26%, while the sugarcane crop showed no signs of water stress based on leaf observations and tensiometer readings at 20-cm depth (data not reported here).

Table 1. Mean irrigation quantities recommended by the three tools for the soil rewetting phase (0-60 DAR) and the rest of the sugarcane cycle (60-360 DAR). DAR represents day after regrowth, CV is the coefficient of variation with three repetitions. Values followed by the same letter (a, b) are not significantly different (P> 0.05)

		T. MET-rec	T. OSI-C	T. OSI-F.	CV%
Rainfall (mm)	0-60 DAR	47	47	47	
	60-360 DAR	871	871	871	
Irrigation (mm)	0-60 DAR	209[a]	149[b]	169[b]	12.7
	60-360 DAR	416[a]	347[b]	324[b]	7.7

This resulted (Figure 2) in slightly higher drainage loss measured at the base of lysimeters on the T.MET plots (only one measurement per treatment). There were four periods during which rainfall was quite low throughout the sugarcane cycle (Table 2 and Figure 2). After a few days without rain, drainage (measured in lysimeters and assessed from the TDR probe and tensiometer readings) became nil or very low, making it possible to calculate AET. The results (Table 2) revealed no significant difference between the three compared irrigation methods.

Table 2. Mean actual evapotranspiration (mm/d) for the three treatments during four periods in which drainage at DZ= 180 cm was nil or very low. Values followed by the same letter are not significantly different (P> 0.05). MET is the maximum evapotranspiration (mm/d). CV is the coefficient of variation with three repetitions

	Rainfall	MET	T.MET-rec	T.OSIRI-C	T. OSIRI- F	CV%
Period 1 (28 d)	19.2	4.5	3.51 [a]	3.57 [a]	3.24[a]	15.1
Period 2 (21 d)	17.2	4.3	3.93 [a]	4.13 [a]	3.68 [a]	15.1
Period 3 (21 d)	5.4	3.3	2.82 [a]	3.15 [a]	2.99 [a]	16.6
Period 4 (36 d)	28	3.6	3.34 [a]	3.04 [a]	3.16 [a]	9.9
Total (106 d)	69.8	3.9	3.40 [a]	3.42 [a]	3.25 [a]	8.3

For the MET and OSIRI treatments, AET values were very close to each other and to the MET values, indicating that both irrigation advice tools were able to meet sugarcane water requirements. While yields were similar for both treatments (Table 3), irrigation water productivity was improved (by about 25%) in the OSIRI-managed plots as compared to the MET-managed plots.

Table 3. Effects of irrigation methods on sugarcane yield components and water productivity. Values followed by the same letter (a, b) are not significantly different (P> 0.05). CV is the coefficient of variation with four repetitions

	T.MET-rec	T.OSI-C	T.OSI-F	CV%
Number of stalks per m²	6.1[a]	6.2[a]	6.1[a]	15.6%
Stalk diameter (cm)	2.8[b]	2.9[a]	2.9[a]	0.9%
Stalk height (m)	2.66[a]	2.69[a]	2.64[a]	4.1%
Sugar concentration (%)	15.0[a]	15.0[a]	15.1[a]	2.0%
Fresh millable stalk (t/ha)	86[a]	88[a]	86[a]	11.0%
Sugar (t/ha)	13.9[a]	14.3[a]	14.1[a]	12.8%
Irrigation water productivity (t/mm)	0.137[a]	0.177[a]	0.174[a]	17.5%

Tables 1, 2 and 3 show that use of the two tested OSIRI irrigation methods, i.e. OSI-C (control, with calculations updated every 5 days) and OSI-F (calculations updated every month), led to very similar results. Monthly updating of OSIRI, as presently done by AES, can be considered suitable for optimising irrigation using this tool.

Comparison between experimental and OSIRI-calculated values. Calculated and measured drainage at DZ = 180 cm over a time course (between 60 DAR and harvest) are plotted in Figure 2 for the three treatments. The observed and calculated values were very similar, regardless of the treatment. Monthly values were also compared in order to obtain 10 periods between 60 and 360 DAR (Figure 2). NE, RMSE and MB values given in Table 4 show that the OSIRI model reasonably well simulated the real situation in the field. Note that these values are of the same magnitude as those reported for many field evaluation studies of water transfer models (Duwig et al., 2003). The linear correlation given in Figure 3 confirms the close agreement between the calculated (DT_c) and measured (DT_O) drainage values for the three treatments, and the regression line is not statistically different from the first bisector.

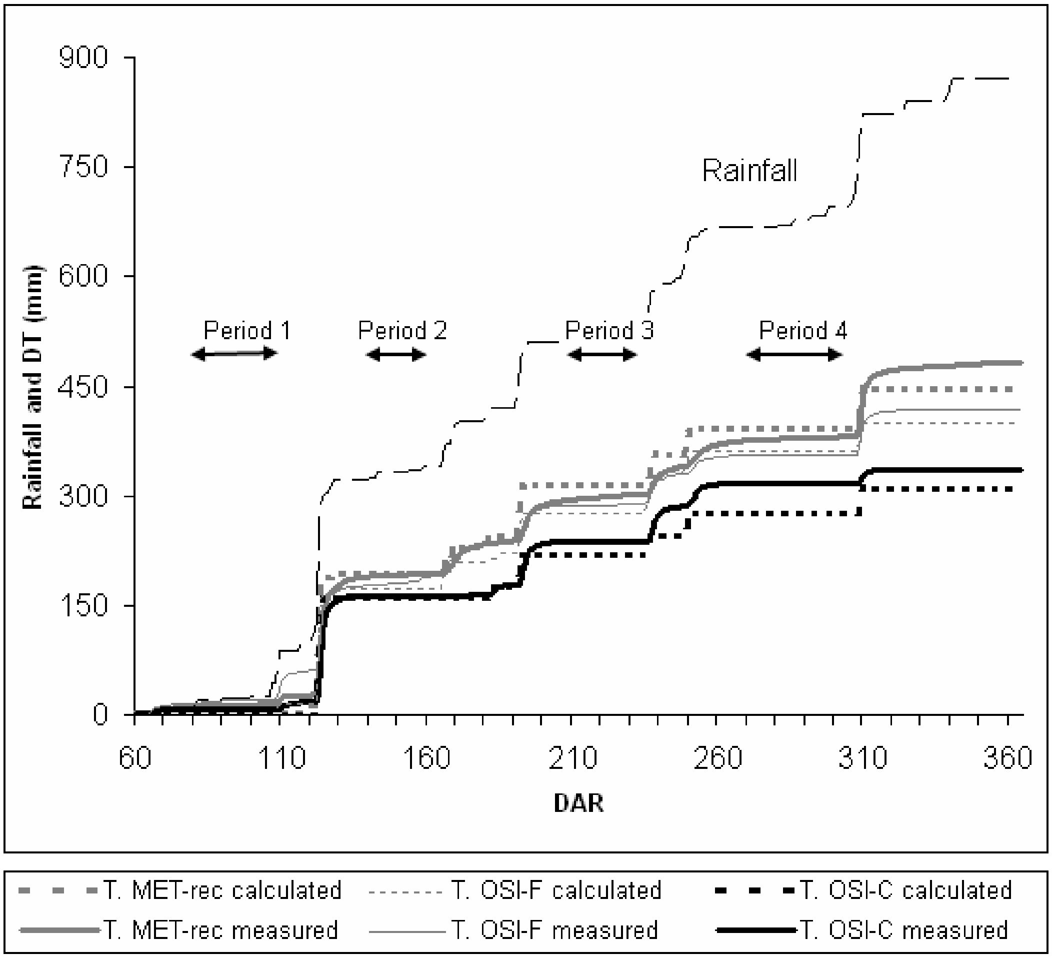


Figure 2. Comparison of cumulative drainage values (DT, mm) measured at the base of lysimeters (DZ = 180 cm) and those calculated by OSIRI for the three treatments. Cumulative rainfall is also plotted as function of DAR (days after regrowth)

Table 4. Statistical results comparing drainage measured and calculated by the OSIRI model at the base of lysimeters for the three treatments. Observations are averaged over 10 1-month periods of sugarcane growth (60-360 DAR)

	Drainage
Number of observations	30
Observed mean (mm/day)	1.37
Mean bias, MB (mm/day)	-0.02
Nash efficiency, NE (-)	0.85
Root mean square error, RMSE (%)	39

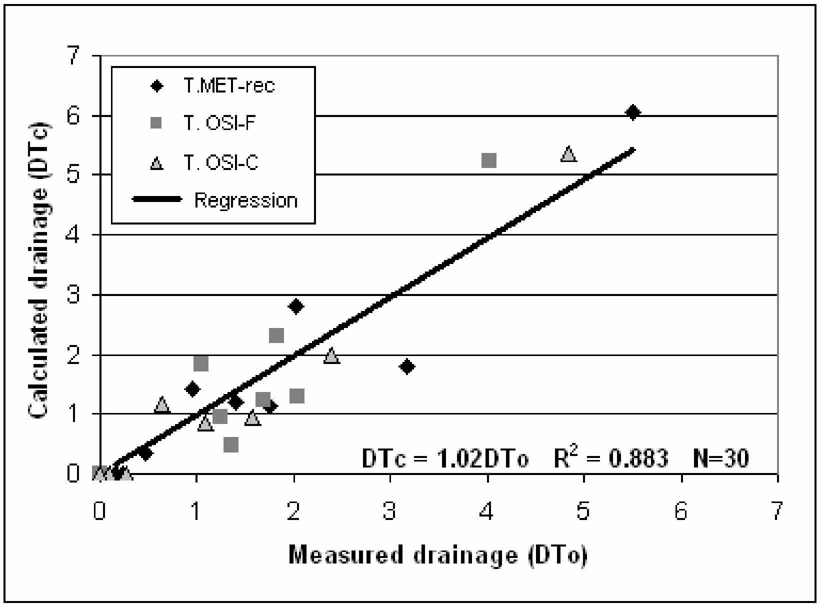


Figure 3. Comparison of calculated (DT_c) and observed (DT_o) drainage at the base of lysimeters (DZ=180 cm) for the three treatments. Mean monthly values (mm/d) between (60 DAR) and harvest (360 DAR). R^2 is the coefficient of determination and N is the number of observations

During the four periods without substantial rain, it was possible to estimate AET from simple field observations of soil water storage variations and according to rainfall and irrigation contributions. This revealed no statistical differences between treatments (Table 2). It also enabled a comparison between measured AET values and those calculated ones by the OSIRI software. Corresponding NE, RMSE and MB values calculated for 36 observations (four periods, three treatments, three repetitions) are given in Table 5. They indicate that OSIRI was also able to accurately simulate actual evapotranspiration.

Table 5. Statistical results comparing observed and OSIRI-calculated AET values in nine plots during four dry periods (see Fig. 3)

	AET
Number of observations	36
Observed mean (mm/day)	3.38
Mean bias, MB (mm/day)	- 0.16
Nash efficiency, NE (-)	0.97
Root mean square error, RMSE (%)	16

Farm survey

Temporal variations in the number of advised farmers and information on irrigation practices. In the survey area, irrigation advice is provided by the equivalent of three AES officers. Although this figure has remained unchanged since 2002, the number of advised farmers nearly doubled between 2002 and 2006 (Figure 4). OSIRI advice was first given at the beginning of the 2004 sugarcane crop season (August-September 2004). The number of farmers using OSIRI drastically increased between 2004 and 2006. Advisers present the different available irrigation advice tools but leave farmers free to choose between them. Figure 4 clearly shows that OSIRI is gradually replacing IRRICANNE (Combres and

Kamiéniarz, 1992), a former local irrigation monitoring tool, and that it has been adopted by a majority of newly advised farmers. However, some farmers still prefer MET recommendations as they are simpler than those provided by OSIRI. Introduction of the OSIRI tool in the Réunion farming community thus clearly enabled a constant number of advisers to provide recommendations to a growing number of farmers. Only six out of 25 of the surveyed farms were equipped with a rain gauge. Very few of them generally record actually applied irrigation doses, which makes it difficult to use OSIRI for optimizing irrigation.

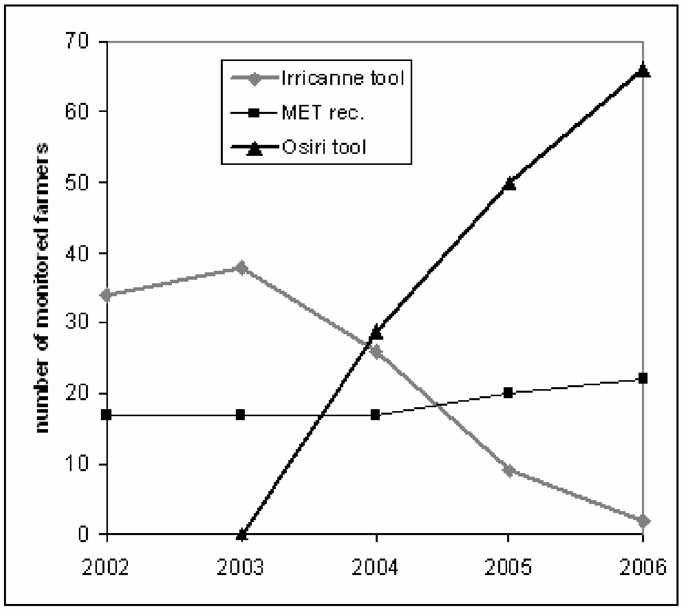


Figure 4. Temporal patterns in the number of sugarcane farmers receiving different types of irrigation advice from three Agricultural Extension Service officers

Acceptability of the OSIRI tool by farmers. A preliminary data analysis showed that there was no noticeable difference in farmers' answers when comparing those surveyed in the southern and western parts of Réunion (Figure 1a). Therefore all the 25 farmers' responses were pooled into one group. Table 6 shows that most farmers considered that: (i) doses recommended by OSIRI met their needs, (ii) OSIRI advice led to a slight reduction in irrigation water application compared with their former practices, and (iii) irrigation was slightly easier to control than before.

Table 6. Opinion of 25 surveyed users on the OSIRI tool. Overall impression (1 = very bad, 2 = bad, 3 = medium, 4 = good, 5 = very good); Recommended doses (range from 1 for too small to 5 for too high); Irrigation dose variations since the beginning of OSIRI use (1 = much more to 5 = much less); Easiness to control irrigation compared with former practices (1 = more difficult to 3 = easier)

	Overall impression about OSIRI	Accuracy of recommended doses	Consumption variation with OSIRI	Easiness to control irrigation
Average (SD)	3.9 (0.64)	2.9 (0.40)	4.1 (0.70)	2.25 (0.44)
Min and max	2 - 5	1-3	3 - 5	2-3
Medium	4	3	4	2
Average opinion	Good	Adequate doses	Drop	A bit easier

These results are very encouraging, especially since they show that the farmers were aware that water application could be decreased by using OSIRI compared with their previous practices, thus meeting one of the main objectives of the new tool—reducing precautionary irrigation without reducing crop yield.

However, the standard deviations (Table 6) obviously show a certain degree of variability in the answers. At least part of this variability (Table 7) could be ascribed to factors such as: age and training type of farmer, programming mode, and type of irrigation advice before using OSIRI. Groups of younger and more trained farmers (AI type) appeared to be slightly more convinced by the advantages of using OSIRI. However, the variability in opinions likely mainly resulted from causes other than those assessed, e.g. human factors associated with the farmer during the survey, or the interviewer. Table 7 also indicates that OSIRI was well accepted and useful for all types of farmers surveyed, irrespective of age, training type and irrigation system.

Table 7. Variability in farmer answers. Overall impression of OSIRI (1 = very bad to 5 = very good); Recommended doses (1 = too small to 5 = too large); Level of irrigation water recommended by OSIRI (1 = much more to 5 = much less); Easiness to control irrigation compared with former practices (1 = more difficult to 3 = easier). Numbers in parentheses indicate standard deviations. “I” indicates farmers with practical irrigation training without agricultural studies and “AI” indicates farmers with basic agricultural studies complemented by practical irrigation training

Explanatory variables		Number of farmers	Overall impression	Recommen-dation accuracy	Consumption variation	Easiness to control irrigation
Age group (years)	<40	14	4.1 (0.47)	3.0 (0.00)	4.0 (0.68)	2.21 (0.43)
	>40	11	3.7 (0.79)	2.8 (0.60)	4.2 (0.75)	2.27 (0.47)
Training type	I	12	3.8 (0.83)	2.8 (0.58)	4.1 (0.67)	2.25 (0.45)
	AI	13	4.1 (0.47)	3.0 (0.00)	4.0 (0.68)	2.21 (0.43)
Former advice	Nothing	12	3.9 (0.83)	2.8 (0.60)	4.1 (0.83)	2.27 (0.47)
	Irricanne	11	4.0 (0.43)	3.0 (0.00)	4.0 (0.60)	2.17 (0.39)
Program-ming	In time	10	3.9 (0.32)	3.0 (0.00)	3.8 (0.63)	1.80 (0.42)
	In volume	14	3.9 (0.83)	2.9 (0.53)	4.3 (0.73)	1.79 (0.43)

Impact of the OSIRI management tool on sugarcane yields. Millable sugarcane yields of five farms selected among the 25 surveyed farms were measured each year for 6 successive years. They are located in the same southern area of Réunion with a maximum distance of 1 km between them to offset climatic variability. During the first 2 years (2001-2002), irrigation was applied without any advice and the equipment was old (removable sprinklers). In 2003, farmers bought new equipment (fixed sprinklers and programming irrigation autotimers), but they did not follow any irrigation advice in 2003 and 2004. Since 2005, these five farmers have been using the OSIRI decision-making tool. Consequently, the whole period (2001-2006) can be separated into three classes of irrigation practices (equipment and advice).

Table 8. Millable yield measured on five farms between 2001 and 2006 for different equipment, climate conditions and irrigation advice. Solar radiation and temperature are daily mean values during the sugarcane growing season. Maximum evapotranspiration (MET) and rainfall are cumulative values. Numbers followed by the same letter (a, b) are not significantly different (P>0.05)

	2001-2002	2003-2004	2005-2006
Equipment, sprinklers	Removable	Fixed	Fixed
Advice	without	without	OSIRI
Solar radiation (J/cm²/d)	1776	1757	1791
Mean temperature (°C)	21.8	21.9	22.0
MET (mm)	1131	1087	1110
Rainfall (mm)	1169	892	864
Millable yield (T/ha)	97.8[a]	112.9[ab]	124.4[b]

Table 8 shows an interesting trend in millable yields from the first to the third period, which cannot be explained by temperature, solar radiation and MET values as they were quite stable. Annual rainfall obviously varied between periods, but irrigation is supposed to supply enough water each year to maintain the sugarcane at optimal evapotranspiration. There was a positive effect (+15%) of the new irrigation equipment acquired in 2003. Although not spectacular or highly significant, a positive effect (+10%) of using OSIRI as a decision-making tool for monitoring irrigation should also be noted. However, the main purpose of OSIRI is not to increase yield but mainly to reduce irrigation delivery, without any yield reduction. It is worth mentioning that these on-farm survey results confirmed those obtained in the detailed field experiment. For the five studied farms, the combined use of new equipment and the OSIRI advice tool led to a significant 27% increase in millable yield.

CONCLUSION

This study was carried out to evaluate the performance of OSIRI, a new decision-making tool for monitoring irrigation. Detailed field measurements in different sprinkler irrigation treatments highlighted that OSIRI recommended lower irrigation applications than the currently used tool, thus reducing drainage loss below the sugarcane root zone without affecting yield. Satisfactory agreement between the measured and OSIRI-calculated actual evapotranspiration and drainage values was obtained. Good concordance was confirmed both for relatively dry conditions (the main reason for developing and using this irrigation tool) and wet conditions leading to high drainage. OSIRI is thus suitable for predicting drainage loss and studying environmental impacts of irrigation, for example. In the studied conditions, updating OSIRI monthly seems enough to optimise irrigation doses, while updating every water roster (5 days) did not improve this parameter or yield. Tests are nevertheless under way to estimate the effects of lowering updating frequencies (3 or 6 months).

Since OSIRI is beginning to be used by farmers, an on-farm survey was conducted with 25 of them in order to test its acceptability and usefulness. Analysis of the results revealed that OSIRI is well accepted by farmers who consider it to be a valuable decision-making tool. Farmers realize that OSIRI can lower irrigation water volumes without reducing sugarcane production. Most of them felt that OSIRI allowed irrigation water savings as compared to the currently used method, without any yield decrease, as clearly shown by the results of the experimental test conducted under controlled conditions.

While there is a sharply increasing demand for the use of this tool in Réunion, its dissemination will clearly be dependent on the capacity of the Agricultural Extension Service to train farmers and on their ability to use the tool thereafter. For proper use of OSIRI (as for most of irrigation advice tools), it is essential to measure local rainfall. In Réunion, only a few farmers are currently equipped with rain gauges. More, rain gauges (even low tech guages) are thus required and farmers should be trained on their use.

OSIRI was developed for sugarcane farmers in Réunion, but it is likely also applicable in other social and physical environments. Studies in different setting are thus essential and would certainly contribute to improving this software tool.

REFERENCES

Bernard, H.; P.F. Chabalier; J.L. Chopart; B. Legube; M. Vauclin. 2005. Assessment of herbicide leaching risk in two tropical soils of Reunion Island (France). J. Env. Qual. 34, 537-543.

Cabelguenne, M.; M. Puech; P. Dehbaeche; N. Bosc; A. Hillaire. 1996. Tactical irrigation management using real time model and weather forecast: experiment on maize. In: Irrigation scheduling: From Theory to Practice. Proceedings of ICID/FAO Workshop, Sept. 1995, Rome, Italy. Water report No. 8, FAO United Nations, Rome, Italy.

Chopart, J.L.; M. Vauclin. 1990. Water balance estimation model: field test and sensitivity analysis. Soil Sci. Soc. Am. J. 54 (5), 1377-1384.

Chopart, J.L.; L. Le Mézo; M. Mézino. 2005. OSIRI user guide. CIRAD, St. Pierre Réunion (France), note CAS103/05-1 (unpubl.), 30 pp.

Chopart, J.L.; M. Mézino; F. Aure; L. Le Mézo; M. Mété; M. Vauclin. 2007. OSIRI: a simple decision-making tool for monitoring irrigation of small farms in heterogeneous environments. Agric. Water Manage. 87, 128-138.

Combres, J.C.; C.Kamiéniarz. 1992. Un logiciel multi-parcelles d’avertissement en irrigation et de gestion des périmètres irrigués. ICID Bulletin 41 (2), 135-152.

Dechmi, F.; E. Playan; J.M. Faci; M. Tejero. 2003a. Analysis of an irrigation district in northeastern Spain. I: Characterisation and water use assessment. Agric. Water Manage. 61, 75-92.

Dechmi, F.; E. Playan; J.M. Faci; M. Tejero; A. Bercero. 2003b. Analysis of an irrigation district in northeastern Spain. II: Irrigation evaluation, simulation and scheduling. Agric. Water Manage. 61, 93-109.

Doorenbos, J.; W.O. Pruit. 1977. Crop water requirements. In: FAO Irrigation and Drainage Paper No. 24, FAO, Rome, Italy, 193 pp.

Duwig, C.; B. Normand; M. Vauclin; G. Vachaud; S.R. Green; T. Becquer. 2003. Evaluation of the WAWE Model for predicting nitrate leaching for two contrasted soil and climatic conditions. Vadose Zone J. 2, 76-89.

Georges, B.A.; H.M. Malano; V.H. Tri; H. Tural. 2004. Using modelling to improve operational performance in the Cu Chi irrigation system, Vietnam. Irrig. and Drain. 53, 237-249.

Inman-Bamber, N.G.; C. Baillie; J. Wilcox. 2002. Tools for improving efficiency of limited water use in sugarcane. In: Proc. of Irrigation Ass. Australia Nat. Conf., Sydney, 21-23 May, pp. 251-259.

Jackson, R.D.; S.B. Idso; R.J. Reginato; P.J. Pinter. 1981. Canopy temperature as a crop stress indicator. Water Resour. Res. 17, 1133-1138.

Ozier-Laffontaine, H. ; Y.M. Cabidoche. 1995. Thickness variations of vertisols for indicating water status in soil and plant. Agric. Water Manage. 28, 149-161.

Rowshon, M.K.; C.Y. Kwok; T.S. Lee. 2003a. GIS-based scheduling and monitoring of irrigation delivery for rice irrigation system. Part I: Scheduling. Agric. Water Manage. 62, 105-116.

Rowshon, M.K.; C.Y. Kwok; T.S. Lee. 2003b. GIS-based scheduling and monitoring of irrigation delivery for rice irrigation system. Part II: Monitoring. Agric. Water Manage. 62, 117-126.

Smith, M. 1992. CROPWAT: A computer program for irrigation planning management. FAO Irrigation and Drainage paper No. 46, FAO Roma, Italy.

Stirzaker, R.J.; P.A. Hutchinson. 2005. Irrigation controlled by a wetting front detector: field evaluation under sprinkler irrigation. Aust. J. Soil Res. 43, 935-943.

Wiedenfeld, B.2004. Scheduling water application on drip irrigated sugarcane. Agric. Water Manage. 64, 169-181.

FEEDBACK BASED CONTROL OF TURFGRASS IRRIGATION IN THE HUMID REGION

Michael D. Dukes[1]
Bernard Cardenas-Lailhacar[2]
Melissa B. Haley[3]

ABSTRACT

At current water use growth rates, supply for future demand is uncertain in many locations of Florida. Rain sensors are required on automatic irrigation systems installed after 1991 in Florida and, recently, commercially available soil moisture sensors for irrigation control have been introduced into the market. This paper summarizes part of the irrigation research carried out in Florida with respect to the use of these sensors and their effectiveness for water conservation in landscape irrigation. Rain sensors and soil moisture sensors are being tested under controlled experimental conditions and under homeowner conditions. Experimental results show that both rain sensors and soil moisture sensors can save water (34%, and up to 92%, respectively) compared to a time-based treatment, when operated under wet weather conditions. Initial results from testing on single family homes show that these technologies have substantial water savings potential. In both plot scale and single family home scale testing, turf quality reduction has not been found when using any of the tested sensors.

INTRODUCTION

In the United States, it is estimated that there are 20 million ha of maintained turfgrass with an economic value of around $40 billion per year (Morris, 2006). In Florida, 1.8 million ha of turf existed in 1991-92 and three-quarters of this acreage was categorized as residential. Industry sales and services amounted to approximately $7 billion value added during that time, ranking only second in value to tourism in the state's economy (Hodges et al., 1994). The increased competition for water resources between urban, recreational, industrial and agricultural users challenges the long-term viability of these industries, as they currently exist.

Florida has the second largest withdrawal of ground water for public supply in the United States (Solley et al., 1998). While agricultural water use has remained relatively flat in recent years, municipal water use has grown (Marella, 1999) due to a population increase rate of more than 1,100 people a day (United States Census Bureau [USCB], 2004a). Nearly 11% of all new home construction in the U.S. occurs in Florida, being the largest fraction of all U.S. home construction that can be attributed to a single state (USCB, 2004b). The majority of these new homes include an in-ground irrigation system for the landscaped area, where the largest proportion is covered with turfgrass (Tampa Bay Water, 2005; Whitcomb, 2005).

[1] Associate Professor, 107 Frazier Rogers Hall, University of Florida, Gainesville, FL 32611; mddukes@ufl.edu
[2] Research Associate, 234 Frazier Rogers Hall, University of Florida, Gainesville, FL 32611; bernardc@ufl.edu
[3] Graduate Research Assistant, 263 Frazier Rogers Hall, University of Florida, Gainesville, FL 32611; mcbaum@ufl.edu

Two recent studies (CQGRD, 2006; Geoplan Center, 2006) concluded that Florida's population will double in 50 years. As a consequence, on the southwest coast most counties from Tampa Bay to the Everglades would be entirely built out, causing a population spillover that will completely urbanize the central peninsula from Ocala to Sebring and from St. Petersburg to Daytona Beach. The east coast; however, will have long become densely packed from Jacksonville to the Keys. South Florida will also become mostly urbanized with the exception of some of the agricultural lands north and south of Lake Okeechobee. Although these population estimates are for a future scenario, currently vast areas of the north-central peninsula and almost all of south Florida have been already declared Water Resource Caution Areas, because water is either scarce or contaminated as defined by Florida's Water Management Districts.

In a comprehensive study of residential water use across the U.S., an average of 59% was attributed to outdoor use with most of that being irrigation (Mayer et al., 1999). In Central-Florida, Haley et al. (2007) found that, on average, irrigation accounted for 64% of the residential water use volume. One reason for this large fraction of non-indoor use was due to homeowner over-irrigation. Thus, at current water use growth rates, supply for future demand is uncertain in Florida.

Qualls et al. (2001) conducted a study in Colorado, testing soil moisture sensors to control turfgrass irrigation when soil tension was beyond a pre-set threshold. The sensor-based systems used an average of 533 mm over the irrigation season compared to the theoretical requirement of 726 mm (27% of water savings). In Florida, Haley et al. (2007) found that setting irrigation timers monthly, according to historical evapotranspiration (ET) requirements, resulted in a 30% irrigation reduction over a 30 month study period. A 50% savings was shown when this irrigation schedule was combined with 65% of the irrigated area under microirrigation, compared to exclusively sprinkler irrigation.

Rain sensors are required on automatic irrigation systems installed after 1991 in Florida and, recently, commercially available soil moisture sensors for irrigation control have been introduced into the market. This paper describes and briefly summarizes part of the irrigation research carried out in Florida with respect to the use of rain sensors and soil moisture sensors and their effectiveness for water conservation in landscape irrigation.

METHODS

Testing on soil moisture sensor controllers and rain sensors is being conducted under controlled plot scale conditions at the University of Florida, Agricultural and Biological Engineering Department Turfgrass Research Facility, in Gainesville. Further testing is being conducted with homeowner cooperators in Pinellas County, Florida. Testing in Gainesville is on bermudagrass and consists of four different soil moisture sensors as well as one type of rain sensor. Testing in Pinellas County consists of one type of soil moisture sensor and one type of rain sensor. Homeowner landscapes consist of mixed ornamentals and St. Augustinegrass lawns. On both sites, irrigation amounts are recorded by flowmeters, weather data are collected to quantify rainfall as well as necessary parameters to calculate reference evapotranspiration (ETo), and routine turf quality measurements are performed.

Plot Testing Site

The Turfgrass Research Facility in Gainesville consists of 72, 3.7 m x 3.7 m plots on a field covered with well established common bermudagrass [*Cynodon dactylon* (L.) Pers]. Each plot is sprinkler irrigated by four quarter-circle pop-up spray heads (Hunter 12Q, Hunter Industries, Inc., San Marcos, CA), with an average application rate of 38 mm/hr at 172 kPa. The experimental area is on an Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) (Thomas et.al, 1985; USDA, 2003).

Four commercially available soil moisture sensors were selected for evaluation (Table 1): Acclima Digital TDT RS-500 (Acclima Inc., Meridian, ID), Watermark 200SS-5 (Irrometer Company, Inc., Riverside, CA), Rain Bird MS-100 (Rain Bird International, Inc., Glendora, CA), and Water Watcher DPS-100 (Water Watcher, Inc., Logan, UT), denoted as AC, IM, RB, and WW, respectively. Each one of these soil moisture sensor systems includes a sensor and a controller that can be adjusted to different volumetric water thresholds. Cardenas-Lailhacar (2006) presented photographs of each controller and the experimental site.

Table 1. Soil moisture sensor brands, models, codes, and controller set point tested at the Agricultural and Biological Engineering Department Turfgrass Research Facility, in Gainesville, FL.

Brand	Model	Code	Controller Set Point
Acclima	TDT RS-500	AC	7% (VWC)
Rain Bird	MS-100	RB	#2.5
Irrometer	200SS-5	IR	#1
Water Watcher	DPS-100	WW	#0

VWC = volumetric water content

As recommended by manufacturers, the RB and WW controllers were set at their indicated thresholds 24 hours after a significant rainfall event (Table 1). The thresholds on RB controllers were set to the relative set point of #2.5 (where #1 is dry and #9 is wet). On the WW, the calibration procedure consisted of setting the knob in the center position (#0), and pushing the calibration button, which allowed auto-calibration. The IM controllers were set at number 1, equivalent to 10 kPa according to the manufacturer, which corresponds to field capacity in this soil (Cardenas-Lailhacar, 2006). The AC controllers were set on their display at a volumetric water content (VWC) of 7%. In addition, a Mini Click rain sensor (Hunter Industries, Inc., San Marcos, CA) was set at 6 mm rainfall threshold. All sensors were connected to residential irrigation timers to bypass scheduled irrigation cycles if soil moisture content or rainfall exceeded the preset threshold.

Table 2 gives the details of the experiment design. Three time-based treatments were established: without sensor, with rain sensor, and a deficit irrigation treatment, set as 60% of the with rain sensor treatment. The four soil moisture sensor brands were tested over 1, 2, and 7-day/week irrigation windows. Finally, non-irrigated plots were also established. Based on a schedule

(Table 3) recommended by Dukes and Haman (2002), all treatments were programmed to apply the same amount of irrigation (except for treatments 2-DWRS and 0-NI). Therefore, differences in water application among treatments occurred when the sensors bypassed scheduled irrigation cycles.

Table 2. Irrigation treatment codes and descriptions for the sensor experiment at the Agricultural and Biological Engineering Department Turfgrass Research Facility, in Gainesville, FL (after Cardenas-Lailhacar et al., 2007).

Treatment Codes	Irrigation Frequency (days/week)	Soil Moisture Sensor Brand or Treatment Description
Time-Based		
2-WOS	2	Without sensor
2-WRS	2	With rain sensor
2-DWRS	2	Deficit WRS = 60% of 2-WRS
SMS-Based		
1-AC	1	Acclima
1-RB	1	Rainbird
1-IM	1	Irrometer
1-WW	1	Water Watcher
2-AC	2	Acclima
2-RB	2	Rainbird
2-IM	2	Irrometer
2-WW	2	Water Watcher
7-AC	7	Acclima
7-RB	7	Rainbird
7-IM	7	Irrometer
7-WW	7	Water Watcher
0-NI	0	Non-irrigated

SMS = soil moisture sensor

Statistical data analyses were performed using the general linear model (GLM) procedure of the Statistical Analysis System software (SAS, 2000). Analysis of Variance was used to determine treatment differences for a completely randomized design. Duncan's Multiple Range Test was used to identify mean differences.

Table 3. Monthly irrigation depth on turfgrass plots to replace historical evapotranspiration and considering effective rainfall, based on Dukes and Haman (2002).

Month	Irrigation depth (mm)
January	0
February	0
March	112
April	112
May	183
June	142
July	137
August	178
September	137
October	122
November	91
December	91
Total	1305

Residential Testing Site

The homes included in this research project are all located in the City of Palm Harbor in Pinellas County (Figure 1), within the South West Florida Water Management District (SWFWMD). Fifty-nine residential cooperators with automatic in-ground irrigation systems have been recruited. The area was divided into four quadrants, based distance from the coast and natural groupings of homes and labeled as follows: Northwest quadrant (L1), Southwest quadrant (L2), Southeast quadrant (L3), Northeast quadrant (L4).

Pinellas County has a humid subtropical climate, with frost and freezing temperatures occurring at least once annually. The average annual rainfall within the SWFWMD is 1350 mm, with 60-65% occurring between in the summer months (SWFWMD, 2005) when evapotranspiration rates are highest. The groundwater supply in southwest Florida comes from the Floridan aquifer. This aquifer is primarily dependant on the rainfall which occurs in the district as the sole source of natural replenishment (SWFWMD, 2005).

A weather station was installed at each of the four locations to measure the climactic parameters. The stations were centered approximately within a 2 km radius of the homes. The station sites are county owned and managed properties, with flat-grassed areas and minimal tree canopy and other structures at least 61 m away if possible. Date, time, relative humidity and temperature (model HMP45C, Vaisala, Inc., Woburn, MA), solar radiation (model LI200X, Li-Cor, Inc., Lincoln, NE), wind speed and direction (model WAS425, Vaisala, Inc., Sunnyvale, CA) and, precipitation (model TE525WS, Texas Electronics, Inc., Dallas, TX), are recorded in 15 minute intervals via a CR10X data logger (Campbell Scientific, Inc., Logan UT).

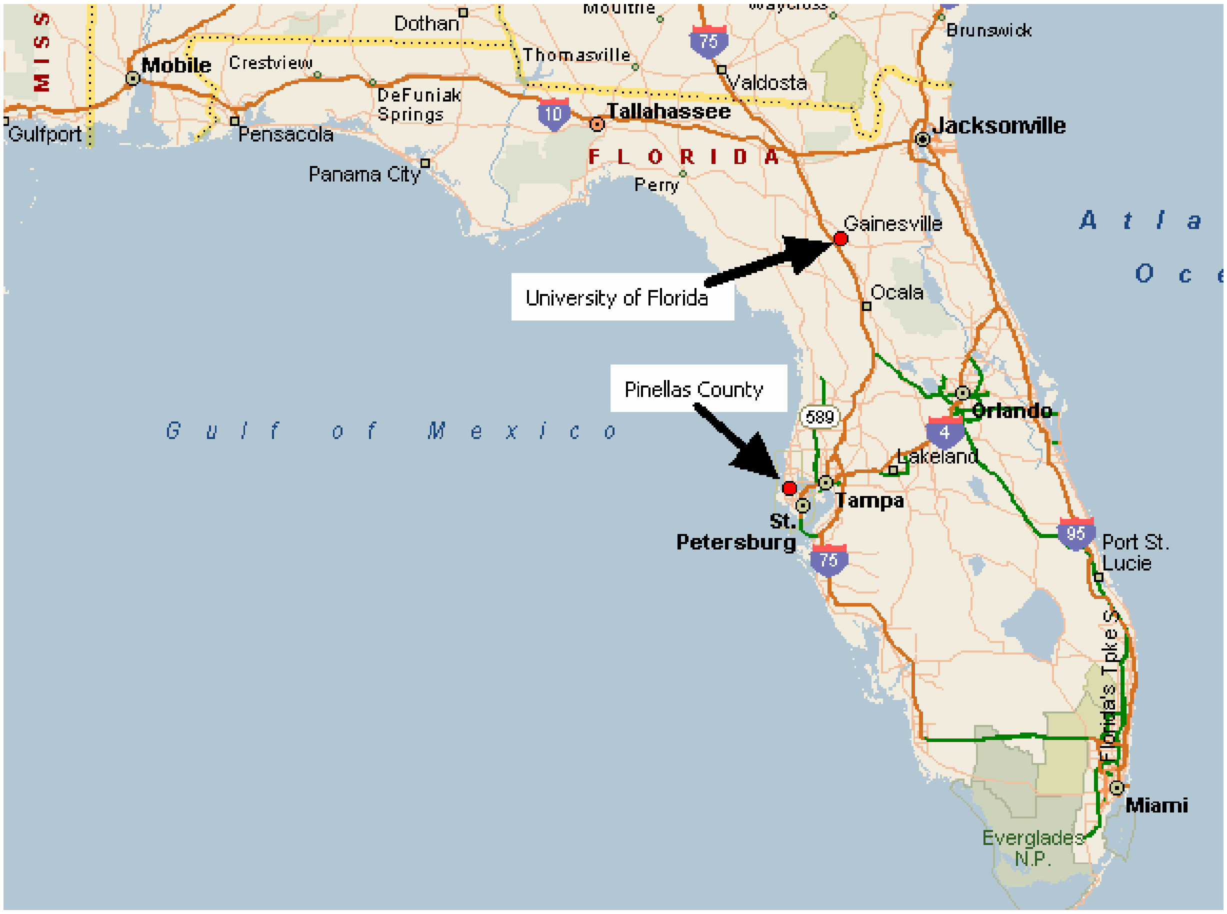


Figure 1. Geographical location of irrigation research sites.

Household water consumption, both total and water used for irrigation is recorded by weekly flow meter readings. All of the homes included in this study obtain water from Pinellas County Utilities. The utility water meter is used to determine the total (indoor plus outdoor) amount of water consumed by the household. A flow meter was also installed in the irrigation mainline to determine the volume of irrigation water used. Positive displacement flow meters were purchased (Baum et al., 2003), and installed by a local contractor, on each of the cooperating residential homes. The meters were installed with no obstruction within approximately ten diameters of the inlet and outlet of the meter when possible. Irrigated area for each home was determined as the pervious area from county records and verified during site visits. The irrigation water use for the homes was calculated as a depth of water applied by dividing the usage volume by the irrigated area.

Irrigation system evaluations were conducted for each home included in the study. The evaluation is a means of quantifying the irrigation system performance by visual inspection and a catch can test in the largest turfgrass landscape area. During this evaluation any maintenance that would compromise the uniformity test was fixed before the testing began. An estimation of system distribution uniformity (DU) was calculated by performing a catch-can test following the Mobile Irrigation Lab Handbook guidelines for Florida (Micker, 1996).

Treatments

The homes were divided into four experimental treatments. The treatment classifications refer to the additional educational materials or sensor based technology incorporated into the systems. Treatment one, T1, homes have an Acclima TDT RS-500 soil moisture sensor. Treatment two, T2, homes have a mini-click rain sensor. Treatment three, T3, homes are a comparison group and do not have any special control technology other than the existing time clock common to all homes. Treatment four, T4, homes have the current irrigation system with a mini-click rain sensor and educational materials.

The educational materials include brochures of outdoor water saving tips developed by the SWFWMD and a customized irrigation run time card. The run time card is based on the home's specific system design and zone layout (i.e. application rates) and gives system run times for each season. The card is laminated and can be affixed to the controller box.

The statistical significant differences between the treatments were performed within SAS (2003). Univariate data analysis was used to determine mean weekly irrigation water use by month. The level of measurement was the range of response from frequency tables with chi-square statistics. The affect of treatment water use and the interactions between month and treatment were analyzed using multivariate analysis. The PROC GLM procedure was used with Duncan's Multiple Range Test to determine mean differences.

RESULTS AND DISCUSSION

Results reported here are for the soil moisture sensor experiment in Gainesville for the July through December 2004, and March through August 2005 time periods. In addition, results for the homes in Pinellas County are reported for the July 2006 through January 2007 time period.

Plot Irrigation Control Sensor Testing

During the testing periods, in both 2004 and 2005, the weather conditions were generally wet; with high frequency rainfall events, and cumulative precipitation of 944 and 732 mm for each respective testing cycle. As a result, sensors were very active, bypassing numerous scheduled irrigation cycles. Table 4 shows the total irrigation applied by the different treatments during both seasons, and a comparison against the control treatment without sensor (2-WOS). The three time-based treatments (2-WOS, 2-WRS, and 2-DWRS) were significantly different from each other during the study period. The treatment with a functional rain sensor, at 6 mm threshold, applied significantly less water (34%) than the without sensor (2-WOS) treatment. The average of time-based treatments applied significantly more water (around two and a half times) compared to the soil moisture sensor-based treatments (1044 vs. 420 mm, respectively). All three irrigation frequencies tested (1, 2, and 7 day/week) were significantly different. The 7-day/week frequency resulted in the least amount of irrigation applied among the soil moisture sensor-based treatments, likely because frequent rain events would result in bypassed irrigation more often than irrigation scheduled at 1 or 2-day/week. All soil moisture sensor-based treatments across the

1, 2, and 7-day/week frequencies showed water savings compared to 2-WOS, which ranged from 27 to 92%.

Performance between different sensor brands was difficult to distinguish. Although the midpoint of all sensors was positioned in the top 7-10 cm of soil in the root zone, there could have been performance differences due to slight variation between sensor placement and/or sensor sizes. In addition, the set point of each brand was not exactly the same. Despite these differences, the Irrometer brand used substantially more water than the other brands (Table 4). This difference is discussed in detail by Cardenas-Lailhacar et al. (2007).

The turf quality across all irrigated treatments exceeded the minimal acceptable during both periods. Moreover, as a consequence of the wet conditions that prevailed, the non-irrigated plots also surpassed the minimal acceptable level. Thus, irrigation was not required to maintain an acceptable quality of the bermudagrass during the testing periods. Based on previous research results (Haley et al., 2007), however, it is unlikely that many homeowners would have ceased irrigation altogether. As a result, the irrigation savings because of the sensors units could have resulted in water conservation on actual homes had these sensors been deployed.

Residential Irrigation Control Sensor Testing

Figure 2 displays the monthly irrigation water application on the cooperating homes. There was a statistically significant difference between the treatment types showing that the incorporation of a sensor clearly decreased water use. As the treatments were applied the plotted lines diverge (note arrows in Figure 2). The soil moisture sensor treatment (T1) shows reduced irrigation relative to the meter only treatment (T3) in September 2006 when the sensor installations commenced. After this point, the cumulative water use for T1 plateaus because of sensors bypassing scheduled events. The difference between the two rain sensor treatments (T2 and T4) is the distribution of the educational materials (T4). These materials were distributed during November, where an initial decrease in T4 water use can be observed.

From Table 5 and Figure 2, it can be observed that the treatment without any additional sensor (T3) consistently used the most irrigation water, with a cumulative amount of 403 mm and a weekly mean consumption of 20 mm. The rain sensor treatment (T2) had cumulative irrigation of 270 mm for the given time period, averaging 9 mm per week. The soil moisture sensor treatment (T1) had total irrigation of 259 mm with a weekly mean use of 6 mm. The treatment with the lowest cumulative water application (227 mm) was that with the rain sensor plus educational materials (T4). However, the mean weekly application on this treatment was not statistically different compared to T1 (soil moisture sensor) or T2 (rain sensor only). It is likely that the irrigation on this treatment (T4) is lower because the materials were provided just prior to winter, when the run-time card suggests a large reduction in run times.

Table 4. Total irrigation depth applied to bermudagrass plots at the Agricultural and Biological Engineering Department Turfgrass Research Facility, in Gainesville, FL, from 20 July through 14 December 2004 and from 25 March through 31 August 2005 (after Cardenas-Lailhacar et al., 2007).

Treatment	Cumulative depth (mm)	Comparisons *A*	Comparisons B	Comparisons *C*	Water savings vs. 2-WORS (%)
Time-Based					
2-WOS	1514	*a*			0
2-WRS	995	*b*			34
2-DWRS	623	*c*			59
Time-Avg	1044		a		
SMS-Based					
1-AC	283				81
1-RB	281				81
1-IM	793				48
1-WW	323				79
1-Avg	420			*b*	
2-AC	348				77
2-RB	188				88
2-IM	1105				27
2-WW	270				82
2-Avg	478			*a*	
7-AC	122				92
7-RB	147				90
7-IM	715				53
7-WW	463				69
7-Avg	362			*c*	
SMS-Avg	420		b		
0-NI	0				100

SMS = soil moisture sensor
Avg = average
Different letters within a column indicate statistical difference at $P<0.0001$ (Duncan's Multiple Range Test).

Table 5. Mean weekly irrigation water use presented by month for each treatment. Duncan letters denote statistical differences at the $P < 0.05$ level.

Month	Mean Weekly Usage (mm)			
	T1	T2	T3	T4
Jul 06	.	3	12	.
Aug 06	.	3	17	.
Sep 06	0	6	8	.
Oct 06	3	16	22	.
Nov 06	9	14	17	.
Dec 06	14	13	15	8
Jan 07	6	11	48	6
Average	6 b	9 ab	20 a	7 b

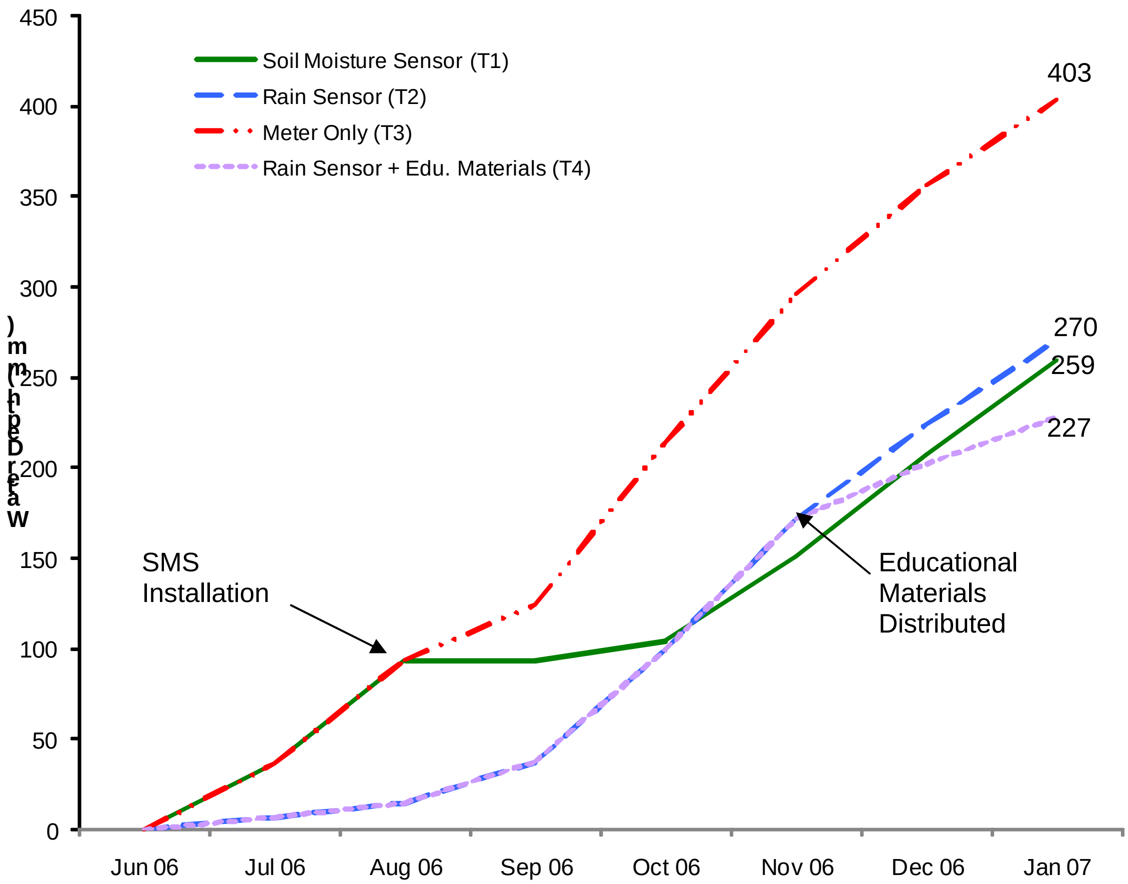


Figure 2. Cumulative water use by treatment.

Of the 59 homes in which evaluations were conducted, 8 homes did not have sufficient areas in which a DU test could be performed. The average DU of the sampling of the 51 homes tested to date is 0.60, ranging from 0.29 to 0.85. Compared to the Irrigation Association distribution uniformity quality ratings for an irrigation system, 59% the homes in this study can be classified as at least good. Initial turf quality ratings were taken for each home during the irrigation evaluations, as a baseline standard of comparison for each home. Continuous seasonal turf quality ratings commenced summer 2006. To date, there have been no notable differences between turf quality and irrigation treatment.

CONCLUSIONS

During relatively wet conditions that are fairly common in Florida and other parts of the Southeast, commercially available soil moisture sensors can significantly reduce irrigation water application when compared to a time-based schedule. Results over a 308 day study period, on turfgrass plots during 2004 and 2005, have shown irrigation water savings of 34% with the use of a rain sensor, and from 69% to 92%, on three of the four soil moisture sensors tested; while maintaining good turf quality.

Preliminary results show that sensors are successful at irrigation water use savings at the single family home level. The treatments with a sensor or educational materials used from 56% to 67% less irrigation water during the data collection period. The treatments with the lowest water use were T1 (soil moisture sensor) and T4 (rain sensor as well as educational materials). During this initial data collection phase, the educational materials were distributed to the T4 homes just prior to the winter months when the run time card recommends a significant reduction in irrigation. The trend of treatment irrigation will need additional seasons to become more apparent.

ACKNOWLEDGEMENTS

The authors thank Engineer Larry Miller, Senior Engineering Technician Danny Burch, and several grad and undergrad students for their assistance and help. This research was supported by Pinellas-Anclotte Basin Board of the Southwest Water Management District, the Florida Nursery and Landscape Growers Association, Florida Turfgrass Association, Florida Department of Agriculture and Consumer Services, Pinellas County Utilities, and the Florida Agricultural Experiment Station.

REFERENCES

Baum, M.C., M.D. Dukes, and D.Z. Haman. 2003. Selection and Use of Water Meters for Irrigation Water Measurement. Florida Cooperative Extension Service, Institute of Food and Life Sciences, ABE 18. University of Florida, Gainesville, FL. Available at: http://edis.ifas.ufl.edu/AE106. Accessed 19 September 2005.

Cardenas-Lailhacar, B. 2006. Sensor-Based Automation of Irrigation of Bermudagrass. M.S. thesis, University of Florida, Gainesville, FL.

Cardenas-Lailhacar, B., M.D. Dukes, and G.L. Miller. 2007. Sensor-based automation of irrigation on bermudagrass during wet weather conditions. *Journal of Irrigation and Drainage Engineering* (Accepted).

CQGRD (Center for Quality Growth and Regional Development). 2006. A Time for leadership: growth management and Florida 2060. Prepared for 1000 Friends of Florida. Georgia Institute of Technology. 41 p. Available at: http://www.1000friendsofflorida.org/PUBS/2060/A-Time-for-Leadership-Report-Final.pdf. Accessed 2 March 2007.

Dukes, M. D. and Haman, D. Z. (2002). "Operation of residential irrigation controllers." CIR1421, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Fla.

Geoplan Center. 2006. Florida 2060; a population distribution scenario for the State of Florida. A research project prepared for 1000 Friends of Florida. Available at: http://www.1000friendsofflorida.org/PUBS/2060/Florida-2060-Report-Final.pdf. Accessed 2 March 2007.

Haley, M.B., M.D. Dukes, and G.L. Miller. 2007. Residential irrigation water use in Central Florida. *Journal of Irrigation and Drainage Engineering*, in press.

Hodges, A.W., J.J. Haydu, P.J. van Blokland, and A.P. Bell. 1994. Contribution of the turfgrass industry to Florida's economy, 1991-1992: A value-added approach. University of Florida, Institute of Food and Agricultural Sciences, Food and Resource economics Department. Economic Report ER.

Marella, R.L. 1999. Water withdrawals, use, discharge, and trends in Florida, 1995. Water-Resources Investigations Report 99-4002, U.S. Geological Survey, Reston, VA.

Mayer, P.W., W.B. DeOreo, E.M. Opitz, J.C. Kiefer, W.Y. Davis, B. Dziegielewski, and J.O. Nelson. 1999. Residential end uses of water. American Water Works Association Research Foundation. Denver, CO.

Micker, J. 1996. Mobile Irrigation Laboratory Urban Irrigation Evaluation Training Manual. U.S. Department of Agriculture. Gainesville, Florida.

Morris, K. 2006. The national turfgrass research initiative. *USGA Turfgrass and Environmental Research Online* 5(10):1-10. Available at: http://usgatero.msu.edu/v05/n10.pdf. Accessed 2 March 2007.

Qualls, R.J., J.M. Scott, and W.B. DeOreo. 2001. Soil moisture sensors for urban landscape irrigation: effectiveness and reliability. *Journal of the American Water Resources Association* 37(3): 547-559.

SAS (Statistical Analysis System). 2003. SAS/STAT User's Guide, Ver. 9.1, SAS Institute, Inc., Cary, N.C.

Solley, W.B., R.R. Pierce, and H.A. Perlman. 1998. Estimated use of water in the United States in 1995. United States Geological Survey Circular 1200. 78 p.

SWFWMD (Southwest Florida Water Management District). 2005. Southwest Florida Water Management District Water Management Plan. Brooksville, FL. Available at: http://www.swfwmd.state.fl.us/about/watermanagementplan/. Accessed 05 March 2007.

Tampa Bay Water. 2005. Evaluating implementation of multiple irrigation and landscape ordinances in the Tampa Bay region. April 2005. Available at: http://www.tampabaywater.org/conservation/reportsdocs.aspx. Accessed 2 March 2007.

Thomas, B.D., E. Cummings, and W.H. Whittstruck. 1985. Soil survey of Alachua County, Florida. USDA/NRCS in cooperation with the University of Florida, Institute of Food and Agricultural Sciences, Soil Science Department and the Florida Department of Agriculture and Consumer Services.

USCB (United States Census Bureau). 2004a. Population estimates. Washington, DC. Available at: http://www.census.gov/popest/estimates.php. Accessed 2 March 2007.

USCB (United States Census Bureau). 2004b. Housing unit estimates. Washington, DC. Available at: http://www.census.gov/popest/housing/. Accessed 2 March 2007.

USDA (United States Department of Agriculture). 2003. "Official soil series descriptions." Natural Resource and Conservation Service, Washington, DC. Available at: http://soils.usda.gov/technical/classification/osd/index.html. Accessed 2 March 2007.

Whitcomb, J. B. 2005. "Florida water rates evaluation of single-family homes. Southwest Florida Water Management District. Available at: http://www.swfwmd.state.fl.us/documents/reports/water_rate_report.pdf. Accessed 2 March 2007.

WATER REQUIREMENTS, IRRIGATION EVALUATION AND EFFICIENCY IN TENERIFE'S CROPS (CANARY ISLANDS, SPAIN)

A. Pérez-Buenafuente[1]
N. Machín-Barroso[1]
J. M. Hernández-Abreu[1]
J. Rodrigo[2]
F. López-Manzanares[1]
J. F. González-Hernández[3]

ABSTRACT

This study, carried out between October 2004 and November 2005 on the island of Tenerife, covers: (1) characterization of the irrigated crops and quantification of the gross irrigation requirements (GIRs) of each crop using surveys; (2) field evaluation of drip/micro, spray and sprinkle irrigation systems to obtain global distribution uniformity (*DU*) as indicated by the Cal Poly ITRC (Irrigation Training and Research Centre, California Polytechnic State University, San Luis Obispo, California, USA); (3) analysis of on farm irrigation efficiency using local climatic data; and (4) inclusion of this data into a Geographic Information System (GIS).

Crop GIRs show high deviations mainly because of the multiple microclimate conditions on the island, the irrigation methods used, the crop systems (greenhouses, etc) and the irrigation management.

Field evaluation provided an average *DU* of 0.83 in drip/micro and spray irrigated banana crops, 0.69 in sprinkle irrigated ones, 0.58 in sprinkle irrigated horticulture and 0.81 for tomato crops (100% drip). Data showed that approximately 30% of the non-uniformity was due to pressure differences in the irrigation system, 3% due to unequal drainage, 7% due to unequal application rates, and 60% was due to other causes (which include manufacturing variation, plugging, and wear).

Irrigation efficiency is around 80% in drip irrigated tomato and banana crops and 75% in sprinkle systems. Data showed that efficiency is slightly lower in greenhouses and mesh greenhouse crops than in non-protected crops basically due to the fact that although protected crops require less water, they receive an equal quantity of water. Inclusion of the data into a GIS makes possible a high level of agronomic water consumption control on the island.

INTRODUCTION

To know the precise agricultural water consumption and the main characteristics of the irrigation systems on an island such as Tenerife (which is similar in its hydrologic behaviour to a continental basin) it is necessary to use this resource properly and to create plans oriented to increase its efficiency.

[1] Área de Aguas, Agricultura, Ganadería y Pesca. Exmo. Cabildo Insular de Tenerife (ECIT). Canary Islands, Spain. agustinpb@mercocanarias.com
[2] Dpto. de Ingeniería, Producción y Economía Agraria. ETSIA. Universidad de La Laguna. Canary Islands, Spain. jrodrigol@eresmas.net
[3] AGRIMAC, S.L. Canary Islands, Spain.

The principal purpose of this study is the characterization of the irrigated lands in Tenerife, to quantify the gross irrigation requirements (GIRs, in m^3/ha and year) of the main crops as well as their statistical distribution by areas and irrigation methods. Furthermore, the average distribution uniformity (*DU*) of the irrigation systems has been determined, detecting the main causes that lead to the lack of uniformity. This data is based on field evaluations in irrigation systems.

Once this first field-phase was completed, the study moved to the estimation, by using climatic data, of the degree of adequacy of the actual consumptions to the water needs of each crop. On farm irrigation efficiencies were estimated for different irrigation methods, crops and areas of the island.

Finally, the resulting GIRs were applied to the existing irrigated land surfaces on the island, using GIS tools and providing the global water consumption of the island, classified for different areas.

In the same way, the present GIRs were compared to the ones appearing in a previous study of agricultural water consumption, which was published 25 years ago (ICSA-GALLUP S.A.,1981), with the final purpose of analyzing the development of irrigation technology evolution on the island during this period.

METHODOLOGY

Study based on surveys

The characterization of irrigated lands and the determination of the GIRs have been made by carrying out a survey on the water users (farmers). During the survey, the installation of the irrigation system and its control system were examined. The water users were asked about their management and maintenance habits, to perform measurement of plant spacing, flow rate of emitters, work pressures, pipe diameters and lengths, etc.

Surveys were made during the 2004-05 campaign and the water-user answers on GIRs, number of crops and harvest duration (in the case of seasonal crops), management criteria and irrigation practices refer to the previous campaign.

The number of surveys needed to determine the parameters of study with enough accuracy was established taking into account the distribution of the variable GIRs that existed in the population, defined by the variation derived from a previous study (ICSA-GALLUP S.A.,1981)

One thousand five (1005) surveys were performed (in the 8 agro-climatic areas in which the island can be divided, Fig 1), of which 959 were analysable (95,4%). The GIR was considered valid in 859 (85,5%) of these surveys. The farms were chosen at random over the crop surface area with or without greenhouses limited by the GIS 2004 Crop Map made by the Exmo. Cabildo de Tenerife (ECIT).

With the final aim of guaranteeing that the geographical distribution of surveys expressed the geographical distribution of each crop, rural GIS crop maps were used to determine the number of surveys to be carried out for a given surface area and the number of surveys per crop.

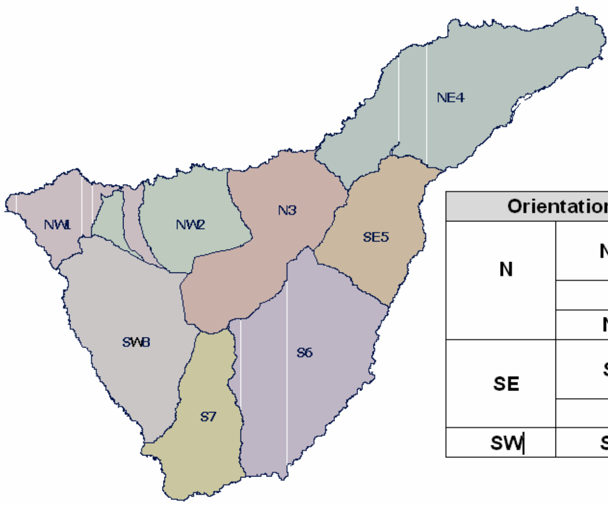
In order to choose the farm to survey, the following criteria were adhered to:

a. The farm could only have one crop and had to have only one irrigation method.

b. The farm had to be homogeneous (e.g.: any surface area with or without greenhouses).

c. The farm could not be adjacent to another that had already been surveyed.

d. The farm was never chosen in relation to the irrigation method used, because one of the aims of the survey was to provide the frequencies of each irrigation method.



Orientation		Zones
N	NW	Zone 1 (Isla Baja)
		Zone 2 (Icod)
	N	Zone 3 (Valle de La Orotava)
	NE	Zone 4 (Tacoronte-Acentejo, Anaga)
SE	SE	Zone 5 (Valle de Güimar)
		Zone 6 (SE Zone)
	S	Zone 7 (Southern Zone)
SW	SW	Zone 8 (SW Zone)

Figure 1. Agro-climatic areas on Tenerife

Each one of the surveyors had equipment consisting of maps of the area, an electronic note-book (PDA, Figure 2) with GPS to locate his own position and the farms to survey as well as to accede to the Map of crops and ortho-photos. To minimize the possibility of inaccurate answers of the farmers about the crop surface area, once the field was surveyed, this parameter was digitalized using the PDA.

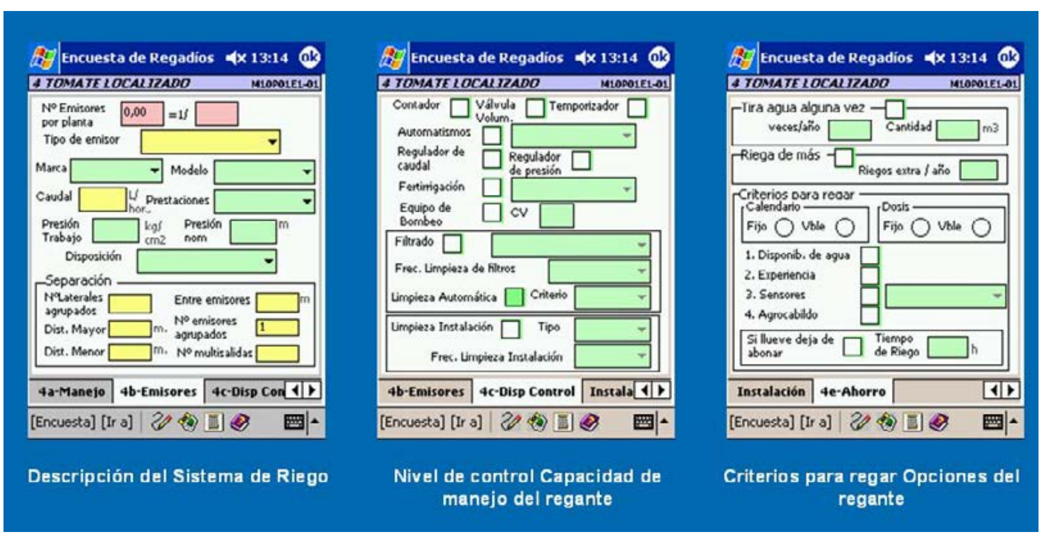


Figure 2. Surveys. Several images from the computer application loaded onto the PDA

Surveys were carried out using a computer application loaded onto the PDA (Fig.2) able to operate with the input data. This was useful for detecting possible mistakes in the water-user answers and to contrast them with complementary equations and valid shift ranks also loaded onto the PDA.

The application automatically created a data base with a new register for each one of the completed surveys. Later on, this data base was downloaded to the principal data base, which was incorporated to the GIS for its analysis.

The staff who carried out the field work (surveys and irrigation evaluations) was Agricultural Engineers. Before this study took place, they were given a specific training course, as recommended by the IRTC (Irrigation Training and Research Centre of the Polytechnic University of California).

Precise knowledge of rainfall during the period in which this study was elaborated (2004) is always required to determine if the year was dry, average or a wet one. In order to determine this, a study based on data from the National Meteorological Institute network rainfall stations on the island was carried out.

Evaluation of the Irrigation Systems

The irrigation system evaluation was developed according to the ITRC method (Fig. 3). One hundred forty two (142) irrigation evaluations were made, 105 were drip/micro and spray systems and 37 were sprinkle systems.

In order to perform the evaluations, the farms with their GIR close to the average value of the agro-climatic area were selected within the survey.

In contrast with the Merrian & Keller method (MERRIAN, 1978), the procedure proposed by the ITRC estimates the global *DU* on the whole farm. Also, this method is able to discriminate different distribution uniformities (*DU*) due to different factors, in such a way that the analysis of them provides the real causes that lead to non-uniformity.

The following factors are taken into account:

a. Lack of uniformity due to pressure differences in the irrigation system ($DU_{\Delta P}$)

$$DU_{\Delta P} = \left(\frac{P_{25\%}}{P} \right)^{x} \quad (1)$$

Where: $P_{25\%}$= Average low-quarter pressures; P= Average of the pressures; x= Discharge exponent of the emitter.

b. Lack of uniformity due to unequal application rates (uneven spacing between plants and/or emitters). (DU_{ed})

$$DU_{ed} = \frac{LAS_{min}}{LAS_{weav}} \quad (2)$$

Where: LAS_{min}= Lowest weekly depth of water applied (mm) on a plot of the farm; $LAS_{we.av}$= Average weekly depth or water, applied (mm) on the whole farm, weighted per surface area.

c. Lack of uniformity due to unequal drainage of the emitter once the irrigation has finished (DU_{dd})

$$DU_{dd} = 1 - \left(\frac{t_{extra}}{t_{avg}} \right) \times \% Surf.affect. \qquad (3)$$

Where: t_{extra}= Extra drainage time (min) once the irrigation has finished; t_{avg} = Average irrigation time (min); *% Surf. affect*:= Percentage of surface area affected by extra drainage.

d. Lack of uniformity due to other causes (which include manufacturing variation, plugging, and wear), DU_{other}.

$$DU_{other} = 1 - \frac{1}{\sqrt{e}} + \frac{1}{\sqrt{e}} \times \left(Avg.\frac{q_{25\%}}{q_{avg}} \right) \qquad (4)$$

Where: $q_{25\%}$= Average low-quarter flow rate (L/h); q_{avg}= Average flow rate (L/h); e = Number of emitters measured per element area.

Figure 3. Irrigation evaluation in a drip irrigated tomato crop in Tenerife

From these partial *DU*s, the global *DU* (DU_{global}) of the irrigation system is estimated using Equation 5. The estimation is based on the element area concept, known as the maximum area in the field that requires water, but within which the variation of distributed water is not important (BURT et al,1997).

$$DU_{global} = 1 - \sqrt{(1 - DU_{\Delta P})^2 + (1 - DU_{ed})^2 + (1 - DU_{dd})^2 + (1 - DU_{other})^2} \qquad (5)$$

Estimation of on farm irrigation efficiency

The theoretical on farm irrigation efficiency was estimated taking into account the following data:

a. The climatic information received by the agro-meteorological stations built by the ECIT on farms placed in the main agricultural areas of the island.

b. The real GIR and the management factor of the water user determined for crops and areas of the island

c. The *DU* obtained for crops and areas of the island, based on irrigation evaluations

d. The leaching requirements based on the water salinity of the samples taken on the farm during irrigation evaluation.

On farm irrigation efficiency is defined as "the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied, expressed as a percentage" (BURT et al, 1997). It was determined by the following equation:

$$Er = \frac{Nb}{Vf} \qquad (6)$$

Where: Er = On farm Irrigation efficiency; Nb = Depth of irrigation water that is beneficially used (mm); Vf = Average depth of irrigation water applied (mm).

Vf was determined from the average GIR weighted per farm size, obtained in the survey phase. In order to get Nb, it was needed to determine the crop evapotranspiration (ETc) and the leaching requirements (LR), discounting rainfall (effective precipitation).

$$Nb = \frac{ETc - Pe}{1 - LR} \qquad (7)$$

ETc was estimated using Equation 8.

$$ETc = ETo \cdot Kc \qquad (8)$$

Where: ETc = Crop evapotranspiration; ETo = Reference crop evapotranspiration; Kc = Crop coefficient. ETo was estimated by the FAO Penman-Monteith equation, based on average monthly values of meteorological data.

Wind speed in net houses was estimated in relation with MÖLLER et al. (2003) in such a way that it could later be used in the FAO Penman-Monteith equation, following FAO advice (ALLEN et al, 1998).

For the crop coefficient (Kc) the values proposed by the FAO in DOOREMBOS (1977) were considered, except in the case of banana plantations where unpublished data determined by the Agricultural Service of ECIT were used.

For the estimation of effective precipitation (Pe) the equations presented by the US Bureau of

Reclamation (SMITH, 1993) were used.

$$Pe = \frac{P}{125}\left(125 - 0{,}2\,P\right) \text{ for P < 250} \qquad (9)$$

Where P = monthly precipitation (mm).

The leaching requirement (LR) was determined from the equations in DOOREMBOS (1977) according to irrigation method. For the EC value, the average value of EC, based on the samples of water taken in each one of the irrigation evaluations made on farm, was chosen.

For the *DU* value, the average value of the DU_{global}, obtained in the irrigation evaluations, was taken.

Once *Er* (Equation 6) was estimated, it was divided in the several factors in which it is composed following this equation:

$$E_r = C_{mg} \times (1 - E) \times DU_{global} \qquad (10)$$

Where: C_{mg}: Management factor (%); *E = Surface losses, evaporation during irrigation in the case of spray or sprinkle irrigation (%).* C_{mg} gives us an idea of how the water user manages the irrigation system, and it can only be determined (Equation 10) once we know the rest of the values. This management factor comprises the losses by percolation as well as those caused by the water user's irrigation management.

The losses by evaporation (*E*) were considered null in the case of drip irrigation. Thus, *Er* factors were completely defined for every component, making clear which factor(s) could be affecting it negatively and their level of intensity.

In the same way, the maintenance factor, C_{mn} (RODRIGO et al, 1992) was estimated, which gives us an idea of the use that the installation receives. This is estimated by Equation 11. In this equation DU_{actual} is the DU_{global} obtained in the irrigation system evaluations, and $DU_{potential}$ is the highest value of *DU* which is possible to achieve with each one of the irrigation methods. These values, shown in Table 1, have been established based on the results obtained in the present study.

$$C_{mn} = \frac{UD_{actual}}{UD_{potential}} \qquad (11)$$

Following this procedure, the necessity to correct the irrigation management habits can be distinguished from the necessity to improve the installation maintenance, and it is even possible to measure the advantages that would produce a hypothetic change in the irrigation system.

Table 1. Results for DU potential for different emitter types in Microirrigation

Irrigation System	Emitter Type	DU potential
Microirrigation	PC and anti drain	97 %
	PC	95 %
	Conventional	90 %

PC = pressure compensating emitter

Determination of the global water consumption of Tenerife: Changes in the last 25 years

The GIRs obtained were incorporated to a GIS that contained the crop map of Tenerife, designed by the ECIT in 2004, constituting a new layer of information. The combination of the data included in both layers made it possible to obtain the global water consumption of Tenerife, divided into crops and areas. This information will be completely necessary in the elaboration of the next Hydrologic Planning of Tenerife (2008).

In the same way, the present GIRs were compared to the ones which appeared in a previous study on agricultural consumption, which was published 25 years ago (ICSA-GALLUP S.A.,1981), with the final purpose of analyzing the development of irrigation technology on the island during that period.

RESULTS, DISCUSSION AND CONCLUSIONS

Study based on surveys

The methodology used in the survey phase, that allows verification and contrast of the results in the field and with the water-user interviewed, allowed us to correct many surveys that would be considered invalid due to multiple causes. (Surveys were filled in using a computer application loaded onto the PDA, able to operate with the input data. This is useful to detect possible mistakes in the water-user answers and to contrast them with complementary equation and valid shift ranks loaded onto the PDA).

The digitalization of the limits of the crop surface area, which was carried out in situ for each one of the surveyed farms (adding these surface areas to a GIS), was absolutely necessary for estimating the GIRs with maximum accuracy.

The use of the PDA during the survey-phase did not only save time and resources, it also avoided transcription mistakes that would be inevitable with traditional methods.

The use of the polygon GIS crop maps in the distribution of the surveys (using GIS tools and based on the percentage of crop surface area that each polygon covered in relation to the whole crop surface area) guaranteed that the geographical distribution of the surveys corresponded to the geographical distribution of each crop. Furthermore, this method made the field work and the control of its efficiency easier.

The adoption of several homogeneity criteria was necessary to consider one farm adequate for being surveyed, because the purpose of this study is to apply the obtained results to the rest of the population and to detect differences in crops, crop systems and irrigation methods.

Irrigation evaluations: ITRC Methodology

The ITRC method, which determines the weight of each factor when referring to the lack of global distribution uniformity, is ideal for the characteristics of the irrigated lands in Tenerife, where diverse parameters co-exist and where it is completely necessary to establish their influence. For instance, the uneven topography of the island, which results in farms with important unevenness (terraces at different levels), affects the irrigation uniformity through pressure differences and the uneven drainage in the process of the system evacuation once the irrigation is finished.

The influence of farm topography over irrigation evaluation is considered a key point of study and it must be analysed, trying not to leave it hidden among other factors.
It has been shown that the ITRC method underestimates the DU in special circumstances that are going to be explained. In relation with this fact, additional estimations and actions have been made as alternatives to the ITRC method. These additional modifications were executed after taking into account their convenience or not in each case:

The non-uniformity caused by an unequal density of emitters per surface area: unequal spaces between plants and emitters (DU_{ed}), is considered a valid parameter, when the irrigation is produced with an invariable number of emitters per plant and in cases of high percentages of shaded areas by the crop. However, when the soil plant covering was less than 70% (e.g. some banana plantations in paired lines with wide aisles), the water demand varied with the density of plantation and in these cases it has been observed that, applying rigorously the ITRC procedure the distribution uniformity was under-estimated due to unequal spaces (DU_{ed}).

This is due to the fact that the uniformity criteria chosen are only based on the applied water depths (mm) and it doesn’t take into account the possible necessity of applying different depths in areas planted with different density (using a different number of emitters or using different application times). In these cases, and always after considering the convenience of the practice of irrigation application, the penalizations imposed by the methodology have been diminished, using, in order to determine the DU_{ed} , the water applied per plant (element) and not the water depth applied.

Figure 4. Greenhouse tomato crop located in terraces.

With reference to the spray and sprinkle irrigation systems, it has been detected that the ITRC procedure doesn't consider the cases in which the farmer, aware of the flow rate differences that exist among the irrigation plots that work under different pressures, corrects it by modifying the irrigation time applied in each one of them. In those circumstances, although the irrigation system shows a deficient DU_{global} (induced by a low $DU_{\Delta P}$), the application of water to the crop does not present such an unfavourable *DU*. In these cases the penalizations imposed by the methodology have been diminished, always after considering the convenience of the management practice, using the real average flow rate of the sprinkles and the application irrigation time in each plot.

Gross irrigation requirements (GIRs) determined

The results of the average values of GIR for each crop, irrigation method, crop system and area, are shown in Tables 2a and 2b.

A systematic analysis of variance for the GIRs obtained for the different areas of study, irrigation methods and main crop systems (with or without greenhouses, with or without soil) has been useful to detect significant differences.

The differences among the GIRs obtained for each sub-group must not be associated only with the irrigation method employed or to the crop system. These values are the result of a combination of multiple factors that directly influence the water consumption. One of those factors is the annual period in which the field is reaped (duration of each crop multiplied by the number of crops reaped successively in the same field in a year), whose average value appears under seasonal crops in Table 2b.

There are some other factors that have influence over the GIRs, they appear in the data base created for the surveys, although they are more difficult to take into account because the segregation of their own samples would diminish the number of surveys related to each option: micro-climatic area (sunny, shading, etc), farm size, irrigation management habits, degree of maintenance of the installation, etc. Also, there are other kinds of factors that could not even be quantified in the present study, but they affect the GIRs in the same way as other factors do (the production obtained, the dedication to maintenance of the farm, etc).

An inversely proportional relationship between the surface area of the field and the variance factor (VF) of the GIR has been detected in almost every one of the studied crops. That is to say that the GIRs obtained show a wider dispersion in small-sized farms in contrast with those of a bigger surface area, which present values that are more in harmony with the average. See Figure 5.

It has been verified that in many areas and crops there are not significant differences between the water consumption in the open air and in greenhouses. This fact influenced, on a low scale, in the efficiency of the irrigation in crops with greenhouses, mainly in banana plantations (refer to the conclusions related to on farm irrigation efficiency).

Banana crops: the GIRs obtained, independently of the irrigation method, have not suffered significant changes in the last 25 years. The GIR that has suffered a more significant change was that for spray irrigation, which has diminished by 10% since the previous study (ICSA-GALLUP,1981).

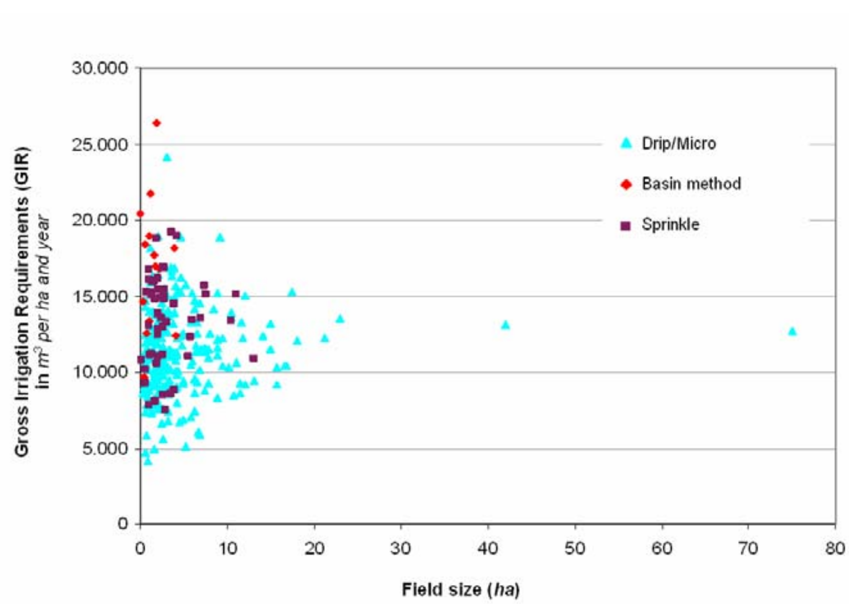


Figure 5. GIR (m^3/*ha and year*) vs. field area (*ha*) in banana plantations for each irrigation method used (drip/micro, spray and level bedded basin).

The average GIR for banana plantations and tomato crops in Tenerife has diminished if we compare the present data with the previous estimations in 1981 (ICSA-GALLUP). Basically, this fact has been caused by the substitution of almost all flood irrigation systems (level bedded basin in banana plantations and furrow irrigation in tomato crops) in benefit of more efficient methods of water use (drip/micro and spray irrigation).

Table 2a. Average GIRs for irrigation method, crop system and number of surveys made

CROP	Irrigation Method	Crop system	AREA 1		AREA 2		AREA 3		AREA 4	
			m^3/ha·year	Nº	m^3/ha·year	Nº	m^3/ha·year	Nº	m^3/ha·year	Nº
BANANA	Basin	Open Air	12,544	1	13,350	1	18,186	9	14,265	4
	Spray	Greenhouse	-	0	-	0	-	0	8,603	2
		Open Air	10,927	2	13,072	3	12,637	8	12,790	3
		AVERAGE	10,927	2	13,072	3	12,637	8	10,983	5
	Drip/Micro	Greenhouse	10,844	10	10,265	3	-	0	8,964	8
		Open Air	11,066	55	8,975	6	8,544	28	10,696	10
		AVERAGE	11,020	65	9,228	9	8,544	28	9,717	18
	AVERAGE		11,020	68	9,611	13	10,796	45	10,170	27
TOMATO	Drip	Open Air	-	0						
		Greenhouse	6,907	1						
		Soilless system (greenhouse)	-	0						
	AVERAGE		6,907	1						
VINEYARD	Drip	Open Air	465	5	1,564	5	725	11	804	30
	Hose	Open Air	-	0	-	0	-	0	995	4
	Furrow	Open Air	-	0	-	0	-	0	960	7
	Basin	Open Air	-	0	-	0	-	0	2,554	1
	AVERAGE		465	5	1,564	5	725	11	821	42

CROP	Irrigation Method	Crop system	AREA 5		AREA 6		AREA 7		AREA 8	
			m^3/ha·year	Nº	m^3/ha·year	Nº	m^3/ha·year	Nº	m^3/ha·year	Nº
BANANA	Basin	Open Air	-	0	-	0	-	0	-	0
	Spray	Greenhouse	-	0	-	0	13,672	7	14,211	3
		Open Air	-	0	-	0	15,610	4	14,169	18
		AVERAGE	-	0	-	0	14,435	11	14,175	21
	Drip/Micro	Greenhouse	11,725	9	9,964	3	11,818	33	12,654	34
		Open Air	7,941	1	12,374	1	11,099	6	14,577	30
		AVERAGE	11,623	10	10,329	4	11,765	39	13,684	64
	AVERAGE		11,623	10	10,329	4	12,028	50	13,795	85
TOMATO	Drip	Open Air			-	0			6,843	3
		Greenhouse			4,518	24			6,128	30
		Soilless system (greenhouse)			4,776	4			-	0
	AVERAGE				4,594	28			6,148	33
VINEYARD	Drip	Open Air	1,797	13	750	12	789	8	1,547	5
	Hose	Open Air	-	0	-	0	-	0	-	0
	Furrow	Open Air	-	0	-	0	-	0	-	0
	Basin	Open Air	-	0	-	0	-	0	-	0
	AVERAGE		1,797	13	750	12	789	8	1,547	5

Distribution of irrigation methods

The present study has allowed us to establish the existing percentages of each irrigation method for each crop and in each location of the island (Table 3), which was previously unknown information and which constitutes a completely necessary tool in order to estimate the global water demand based on crop surface areas and GIRs.

Thanks to a sample of 100% farms in some model areas, it was verified that the obtained percentages of each irrigation method (chosen at random) coincided with the actual distribution of them in the area. In Table 3 these percentages appear for each area and main crop, distinguishing between greenhouse and open air crops.

Irrigation uniformity

Irrigation uniformity in the drip/micro systems by crops: The average global *DU* of the drip/micro irrigation systems in Tenerife, determined by the ITRC procedure is over 80%: 83% in banana plantations and 81% in tomato crops.

Compared with the results of the evaluations made by the California State Polytechnic University, San Luis Obispo, California, USA (Cal Poly) in 260 farms from Central California, which provided an average global DU of 85% in drip and 80% in spray (BURT,2005), the values obtained in Tenerife in tomato farms and banana plantations can be considered as adequate ones.

The frequency of renovation of the irrigation systems and the relatively small size of the farms (in relation with the evaluated Californian farms) constitute the key points to these good uniformities obtained in Tenerife.

Table 2b. Average GIRs per irrigation method and crop system and number of surveys made

CROP	Irrigation Method	Crop System	NORTHERN AREA			SOUTHERN AREA		
			m^3/ha·year	Nº	*Average Growing Period (months/year)*	m^3/ha·year	Nº	*Average Growing Period (months/year)*
POTATOES	**Sprinkle**	Open Air	5,533	*39*	*6.4*	3,769	*40*	*4.6*
	Drip/Micro	Open Air	6,092	*7*		4,711	*7*	
	Hose	Open Air	10,542	*4*		4,560	*7*	
	Furrow	Open Air	3,091	*22*		4,109	*6*	
	AVERAGE		**5,399**	*72*		**3,839**	*60*	
VEGETABLE ROW CROPS (may include potatoes)	**Sprinkle**	Greenhouse	3,508	*2*	*10.49*	7,000	*1*	*9.84*
		Open Air	6,561	*28*	*9.35*	4,220	*3*	*8.70*
		AVERAGE	6,004	*30*	*9.42*	5,284	*4*	*8.98*
	Drip/Micro	Greenhouse	8,706	*23*	*11.16*	7,234	*13*	*7.80*
		Open Air	7,194	*11*	*8.57*	7,910	*12*	*6.55*
		AVERAGE	8,088	*34*	*10.32*	7,602	*25*	*7.23*
	Hose	Open Air	12,243	*8*	*10.55*	-	*0*	-
	Furrow	Open Air	5,029	*8*	*9.52*	-	*0*	-
	AVERAGE		**6,693**	*80*	*9.39*	**6,821**	*29*	*7.01*
SUBTROPICAL TREES AND CITRUS	**Basin**	Open Air	5,582	*1*		13,897	*2*	
		Greenhouse	-	*0*		-	*0*	
		AVERAGE	5,582	*1*		13,897	*0*	
	Sprinkle	Open Air	5,986	*5*		7,347	*1*	
		Greenhouse	-	*0*		-	*0*	
		AVERAGE	5,986	*5*		7,347	*1*	
	Drip/Micro	Open Air	3,518	*17*		5,167	*19*	
		Greenhouse	7,661	*5*		8,036	*10*	
		AVERAGE	4,363	*22*		6,187	*29*	
	AVERAGE		**4,830**	*28*		**6,492**	*32*	

CROP	Irrigation Method	Crop System	NORTHERN AREA m³/ha·year	Nº	Average Growing Period (months/year)	SOUTHERN AREA m³/ha·year	Nº	Average Growing Period (months/year)
FLOWERS AND ORNAMENTAL PLANTS	**Sprinkle**	Open Air	6,541	*8*		-	*0*	
		Greenhouse	7,721	*3*		-	*0*	
		AVERAGE	6,801	*11*		-	*0*	
	Drip/Micro	Open Air	5,268	*11*		9,407	*3*	
		Greenhouse	8,868	*16*		13,564	*4*	
		AVERAGE	6,894	*27*		10,851	*7*	
	Furrow	Open Air	10,800	*1*		-	*0*	
	Drip	Soilless system (greenhouse)	9,581	*1*		-	*0*	
	AVERAGE		**7,005**	*40*		**10,851**	*7*	
SMALL FAMILY ORCHARDS	**Sprinkle**	Open Air	5,635	*7*		1,571	*1*	
	Drip/Micro	Open Air	5,643	*5*		3,263	*5*	
	Hose	Open Air	2,941	*18*		3,410	*3*	
	Furrow	Open Air	4,680	*15*		11,520	*1*	
	Several	Open Air	8,659	*18*		6,010	*1*	
	AVERAGE		**7,005**	*40*		**10,851**	*7*	

In the case of banana plantations we have to add the great number of emitters per plant (between 6 and 12), which produces an increase of the global *DU* although the emitter CV.
In the tomato crops we have to add the quality of the drip emitters used, that in 95% of the cases were PC and in 85% were anti-drain.

The average global *DU* obtained in drip/micro irrigation systems employed in subtropical trees and citrus is 78%, slightly lower than in banana plantations and tomato crops because of the existence of some deficiently attended farms.

Table 3. Distribution of the irrigation methods by location and crops

CROP	Irrigation Method	Crop System	Northern Area % surface	Southern Area % surface
FAMILY HORTICULTURE	**Sprinkle**	Open Air	17.5%	14.3%
	Microirrig.	Open Air	12.5%	71.4%
	Hose	Open Air	45.0%	42.9%
	Furrow	Open Air	37.5%	14.3%
	Several	Open Air	45.0%	14.3%
	TOTAL		100.0%	100.0%
SUBTROPICAL TREES	**Surface**	Open Air	3.6%	6.3%
		Greenhouse	0.0%	0.0%
		TOTAL	3.6%	0.0%
	Sprinkle	Open Air	17.9%	3.1%
		Greenhouse	0.0%	0.0%
		TOTAL	17.9%	3.1%
	Micro Irrigation	Open Air	60.7%	59.4%
		Greenhouse	17.9%	31.3%

CROP	Irrigation Method	Crop System	Northern Area % surface	Southern Area % surface
POTATO CROP	**Sprinkle**	Open Air	54.2%	66.7%
	Microirrig.	Open Air	9.7%	11.7%
	Hose	Open Air	5.6%	11.7%
	Furrow	Open Air	30.6%	10.0%
	TOTAL		100.0%	100.0%
INTENSIVE HORTICULTURE	**Sprinkle**	Greenhouse	2.5%	3.4%
		Open Air	35.0%	10.3%
		TOTAL	37.5%	13.8%
	Micro Irrigation	Greenhouse	28.8%	44.8%
		Open Air	13.8%	41.4%
		TOTAL	42.5%	86.2%
	Hose	Open Air	10.0%	0.0%
	Furrow	Open Air	10.0%	0.0%

		TOTAL	78.6%	90.6%		**TOTAL**	100.0%	100.0%
	TOTAL		100.0%	100.0%				
FLOWERS AND ORNAMENTAL PLANTS	**Sprinkle**	Open Air	20.0%	0.0%				
		Greenhouse	7.5%	0.0%				
		Total	27.5%	0.0%				
	Micro irrigation	Open Air	27.5%	42.9%				
		Greenhouse	40.0%	57.1%				
		Total	67.5%	100.0%				
	Furrow	Open Air	2.5%	0.0%				
	Microirrig. Hydroponic	Open Air	2.5%	0.0%				
	TOTAL		100.0%	100.0%				

The global *DU* in the drip/micro irrigation systems used in vineyards is 77% due to the same reasons that have been explained in relation with sub-tropical fruit trees. Here, we have to add the low number of emitters per plant, mainly only 1.

In the drip/micro irrigation systems employed in vegetable crops, ornamental plants and potatoes, in which in the majority of cases the number of emitters per plant is less than 1, the average global *DU* is under 70% (68%). The improvement of the global *DU* of the drip/micro irrigation systems in these crops makes necessary the employment of pressure compensating emitters (PC) and, in same cases, anti-drain emitters with low manufacturing variation coefficients.

Factors that produce non-uniformity in drip/micro irrigation systems: Between 50% (in banana plantations and fruit trees) and 70% (in vineyards) of the global non-uniformity is derived from the DU_{others} (which include plugging, emitter manufacturing variation, wear and many other factors that would cause flow rate differences among emitters even though the emitters are all at the same pressure). This factor can be corrected using good quality emitters and with a good maintenance and management of the installation, in order to avoid plugging and delay its deterioration.

Between 22% (in tomato) and 38% (in fruit trees) of the global non-uniformity is due to the $DU_{\Delta P}$ component. This factor can be corrected firstly with an adequate installation design. Furthermore, it is necessary to make a correct use of valves and pressure regulators, to frequently estimate and control the pressure in the system and/or the use of PC emitters.

The 0.6% (in vegetables), 3.4% (in tomato) and 7.4% (in banana plantations) of the global non-uniformity is derived from the DU_{dd}, produced by the unequal drip drainage, occurred during the evacuation of the pipes once the irrigation is finished, through the drips which are situated in the lowest points of the installation. The correction of this factor can be fulfilled by the replacement of those emitters with anti drainage ones, longer application irrigation and the reduction of size and slope within the irrigation sub-units.

The 2.3% (in vineyards), 4.6% (in vegetables), 6% (in fruit-trees), and 8% (in tomato and banana plantations) of the global non-uniformity is derived from the DU_{ed}, provoked by the application of unequal water depth originated in variations in plant spacing and/or emitter spacing that affect the number of emitters per unit of surface area.

These values can be compared to those obtained in the evaluations made by the Cal Poly in 260 farms in central California, in which 45% of the non-uniformity was a consequence of pressure differences, 52% was derived from other causes, 1% was due to unequal drainage and 2% was due to unequal application of water depth (BURT, 2005).

Table 4. Irrigation Uniformity

Crop		$DU_{\Delta p}$	DU_{ed}	DU_{dd}	DU_{other}	DU_{global}	Nº Evaluations
Banana Drip/Micro	**Average**	92,66%	98,25%	98,30%	87,78%	83,62%	**43**
	Standard desv.	7,95%	4,50%	2,43%	9,74%	11,13%	
Tomato Drip/Micro	**Average**	94,57%	98,03%	99,19%	84,10%	81,18%	**14**
	Standard desv.	5,53%	4,40%	1,30%	9,09%	7,85%	
Horticultura Drip/Micro	**Average**	88,82%	98,16%	99,76%	72,99%	68,25%	**20**
	Standard desv.	9,41%	5,68%	0,55%	20,88%	19,68%	
Vineyard Drip/Micro	**Average**	93,42%	99,37%	99,11%	80,61%	77,85%	**19**
	Standard desv.	8,45%	2,73%	2,03%	18,96%	19,20%	
Subtropical Trees Drip/Micro	**Average**	89,13%	98,33%	99,73%	84,33%	78,88%	**9**
	Standard desv.	7,95%	5,00%	0,51%	10,15%	10,10%	
Platanera Spray	**Average**	87,26	99,52%	99,06%	73,07%	69,11%	**16**
	Standard desv.	8,09	1,32%	3,75%	7,07%	7,84%	
Horticultura Sprinkle	**Average**	93,67%	100,00%	99,79%	59,71%	58,60%	**21**
	Standard desv.	6,52%	0,00%	0,91%	20,63%	20,38%	

Irrigation uniformity in spray and sprinkle irrigation systems: The average global *DU* of the spray irrigation systems in Tenerife, obtained by means of the ITRC procedure (BURT,2004) is 69% in banana plantations (butterfly type of spray) and 58% in vegetable crops (employment of a wide variety of sprays and sprinklers).

Once some modifications were considered in relation with the *DU* determined in banana plantations (fundamentally based on the use of irrigation volumes instead of flow rate, and the suppression of the aero distribution uniformity test), it was estimated that a global *DU* of 76% in spray systems in banana plantations is a value closer to reality.

The lowest global *DU* observed in the vegetable crops is a consequence of the employment (in half of the cases) of gun sprinklers with wetted diameters over 15 m and 100% overlap. These circles, combined with the desired structure of the farms occupied by vegetables, together with its small size, the wind and its disposition in terraces, are incapable of distributing water uniformly. It is estimated that in these crops, the redistribution of water once it is infiltrated in the soil plays a crucial role that balances the non-uniformity of the sprinklers.

Factors that produce non-uniformity in spray and sprinkle irrigation systems: In the spray used in banana plantations 31% of the non-uniformity is derived from pressure differences, 65.5% is a consequence of other causes (where manufacturing variation of sprays, their wear and possible plugging are included), 2.3% due to unequal drainage and 1.1% due to unequal application of water depth.

In the spray and sprinklers used in vegetables, 13.5% of the non-uniformity is derived from pressure differences, 86% due to other causes (defined in the previous paragraph) and 0.5% due to unequal drainage.

On farm irrigation efficiency

Banana plantations with drip/micro irrigation: On farm Irrigation efficiency of the drip/micro irrigation systems in banana plantations can obtain values close to 75%, a level achieved by tomato fields in the open air in agro-climate area Zone 7 (S-7).

The average on farm irrigation efficiency determined for the drip/micro irrigation systems for banana plantations is, approximately, that of 70% in the crops in the open air and 62% in greenhouse cultivation.

Greenhouse banana plantations are irrigated in a less efficient way than in the open air due to the fact that they are given a similar quantity of water, registering lower water demands. Although in several cases the GIR of the greenhouse banana plantations is relatively inferior to that in the open air, this difference cannot balance the differences of water demand between both cases.
In Zone 4 (NE-4) and Zone 7 (S-7) areas the irrigation efficiency in greenhouse cultivation is 10 and 15% inferior, respectively, compared with the efficiency in crops in the open air. In the NW-1 area it is 20% inferior. This circumstance doesn't take place, however in the SW-8 area, where the irrigation corresponds to the diverse necessities with or without greenhouses.

The lowest on farm irrigation efficiencies in banana plantations in the open air and with drip/micro irrigation take place in Zone 3 (N-3) area where the efficiency is inferior to 50%. In this area the irrigation of the banana plantations is almost the same as that in the rest of the northern area and however the average values of evapotranspiration are 20% inferior.

Tomato: The average value for on farm irrigation efficiency in tomato crops in greenhouses is higher in the SE orientated areas (Zone 6, SE-6 and Zone 7, SE-7), with an average efficiency close to 80%, than in the SW orientated areas (Zone 8, SW-8) where the average efficiency is inferior to 60%. In the SW orientated areas the irrigation is fulfilled with superior GIRs than the ones used in the SE orientated areas, although lower irrigation necessities were determined (mainly because of less wind)

The difference in efficiency between both orientated areas is due to the management factor, which in SE orientated areas reaches 95% (the GIRs are remarkably similar to the water needs) while in SW orientated areas it is inferior to 70%.

Irrigation management factor

Banana plantations with drip/micro irrigation: Irrigation management is deficient in the banana plantations in greenhouses, above all in Zone 1 (NW-1) and Zone 7 (S-7) areas, because in these areas the irrigation method is not efficient due to management factors and not for reasons of distribution uniformity.

Irrigation management is deficient in banana plantations in the open air in Zone 3 (N-3) area, in the same way. The low efficiency is due to irrigation management although, in this case there is also a problem of distribution uniformity that contributes to reduce efficiency.

Banana plantations with spray irrigation: The result of the average management of the spray irrigation systems in banana plantations is around 75%. In Zone 8 (SW-8) area there is excellent management of the spray, with an excellent result for management (93% in crops in the open air). The lack of efficiency produced in this area is derived from the limitations of the method and it can't be blamed on poor irrigation management.

In Zone 3 (N-3) area there is the worst irrigation management (44%). The lack of efficiency is due to deficient irrigation management and not to low distribution uniformity.

Tomato: The difference in efficiency between the SW and SE areas is derived from the management factor, which in the SE area reaches 95% (the GIRs adjust themselves in an extraordinary way to the water needs) while in the SW area it is inferior to 70%.

Installation maintenance factor

Banana plantations with drip/micro irrigation: Zone 3 (N-3) area has the lowest average value with reference to installation maintenance (under 80%), that is, the irrigation application uniformity is remarkably lower than what it could be. Zones 7, 1 and 2 have average values that are superior to 90%, which indicates that their systems work according to their potential characteristics. In the rest of the areas the management value varies between an average of 85% and 90%.

Banana plantations with spray irrigation: Zone (S-7) area has the lowest average maintenance value within the spray irrigation installations (79.6%). The uniformity of irrigation is 20% inferior to that which could be obtained with good maintenance of the installation. In the rest of the areas the average value for the maintenance result is superior to 90%.

Tomato: Although the average global uniformity value (DU_{global}) of the drip irrigation systems used in the tomato crop is relatively high (80% and 82% in the SW and SE areas), it is considered that, being basically PC and anti-drain emitters, they could achieve values close to 95% in the best conditions (highest value estimated in several tomato farms evaluated, in a soil-less system). Taking this value as the potential *DU*, the average maintenance result is approximately 85% in both crop areas.

FINANCIAL HELP AND THANKS

This study is included in the Collaboration Agreement subscribed by the Canary Government and the ECIT for the execution of the sectional sub-program of rural and agricultural irrigation tools, co-financed by FEOGA Orientation of the EU.

REFERENCES

Allen R.G.; L. S. Pereira; D. Raes; M. Smith. 1998. Crop Evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. FAO. ISBN 92-5-104219-5.

Área De Aguas Y Agricultura, ECIT; Dirección General De Estructuras Agrarias, Gobierno De Canarias. 2004. Actualización del Mapa de Cultivos de la Isla de Tenerife - Campaña Agrícola 2003/2004.

Brouwer, C.; A. Goffeau; M. Heibloem. 1985. Irrigation Water Management: Introduction to irrigation. FAO Irrigation and drainage paper 3. FAO.

Burt, C.M. 2005. Evaluación rápida en el campo de la uniformidad de distribución de goteo y de micro-aspersión. Reunión Internacional sobre Avances en Riego Localizado. Puerto de la Cruz. Tenerife. 2002. Monografías INIA: Serie Agrícola Nº17 – 2005.

BURT, C.M.; R. E. WALKER; S. W. STYLES; J. PARRISH. 2004. Irrigation Evaluation. Irrigation Training and Research Centre (ITRC). Dept. of Agricultural Engineering. California Polytechnic State University. San Luis Obispo. California.

Burt, C.M.; A. J. Clemmens; T. S. Strelkoff; K. H. Solomon; R. D. Bliesner; L. A. Hardy; T. A. Howell; D. E. Eisenhauer. 1997. Irrigation Performance Measures: Efficiency and Uniformity. Journal of Irrigation and Drainage Engineering. Nov. /Dec. Vol. 123. NO. 6. ASCE.

Doorenbos, J.; W. O. Pruitt. 1977. Crop water requirements. FAO Irrigation and Drainage Paper 24, (Rev.) FAO.

Icsa-Gallup, S.A. 1981. Estudio por encuesta de los consumos actuales de agua en la agricultura de la isla de Tenerife. Encargo del I.R.Y.D.A.

Merrian, J.L.; J. Keller. 1978. Farm Irrigation Systems Evaluation: A guide for management. Utah State University.

Möller, M; J. Tanny; S. Cohen; M. Teitel. 2003. Micrometeorological characterization in a screenhouse. Acta Horticulturae, 614: 445 – 451.

Rodrigo López, J.; J. M. Hernandez Abreu; A. Pérez Regalado; J. F. González Hernandez. 1992. Riego Localizado. Editorial Mundi-Prensa.

Smith, M. 1993. Cropwat. Programa de ordenador para planificar y manejar el riego. FAO Irrigation and drainage paper 46. FAO. ISBN 92-5-303106-9.

USING WIRELESS TECHNOLOGY TO REDUCE WATER USE IN RICE PRODUCTION

Earl D. Vories[1]
Daniel K. Fisher[2]
Phil L. Tacker[3]
Kenneth A. Sudduth[4]

ABSTRACT

While rice is produced in some parts of the world in an upland, rainfed culture, almost all US-produced rice is grown with flood irrigation. In the dry-seeding system commonly used in the midsouthern US, the crop is usually flooded at approximately the V-4 (early tillering) growth stage and a continuous flood is maintained until after heading. The total amount of water used in rice production is quite large, and soil, fertilizers, and pesticides can be carried in the runoff from agricultural fields. Flood depth affects most aspects of flooded rice production, and remote monitoring of the flood depth could be quite valuable to many producers. The objective of this research is to develop and test a system for monitoring water depths in rice fields and alerting the producer so that less labor and energy is required to efficiently manage flood-irrigated rice. A prototype monitoring station was designed to measure water depth in a flooded rice field and transmit the information over a wireless link. A similar sensor and circuit performed satisfactorily in a raingage in 2006. In 2007, prototype monitoring stations will be installed in production rice fields. Concurrently with sensor durability testing, tests will be conducted to determine the limits of the wireless communication system. With daily reports of the water status in each paddy, field visits can be reduced. Over-pumping should be minimized by allowing better scheduling of field visits to stop the pump, and future systems should work with automatic pump control systems to stop the pump before runoff occurs.

INTRODUCTION AND BACKGROUND

While rice is produced in some parts of the world in an upland, rainfed culture, almost all US-produced rice is grown with flood irrigation. In the dry-seeding system commonly used in the midsouthern US, the crop is usually flooded at approximately the V-4 (early tillering) growth stage (Counce et al., 2000) and a continuous flood is maintained until after heading. Figure 1 contains an aerial view of a typical midsouthern US rice field. In 2005, more than 1.6 million acres of rice were planted in Arkansas, 49% of the total US crop (NASS, 2005). Vories et al. (2006) reported irrigation amounts applied to 33 Arkansas rice fields during 2003 - 2005 ranged from 18 to 56 inches. The average amount was 31 inches, more than double the amount typically

[1] Agricultural Engineer, USDA-ARS Cropping Systems and Water Quality Research Unit; P.O. Box 160, Portageville, MO 63873; Earl.Vories@ars.usda.gov
[2] Agricultural Engineer, USDA-ARS Application and Production Technology Research Unit; P.O. Box 36, Stoneville, MS 38776; DKFisher@msa-stoneville.ars.usda.gov
[3] Extension Engineer, University of Arkansas Biological and Agricultural Engineering-Extension; P.O. Box 391, Little Rock AR 72203; PTacker@uaex.edu
[4] Agricultural Engineer, USDA-ARS Cropping Systems and Water Quality Research Unit; Rm 269 Ag. Eng. Bldg, Columbia MO 65211; Ken.Sudduth@ars.usda.gov

applied to other irrigated crops in the state (Hogan et al., 2007). The total amount of water used in rice production is quite large, and currently some rice growing areas of Arkansas, Louisiana, Texas, and California are suffering from serious water problems.

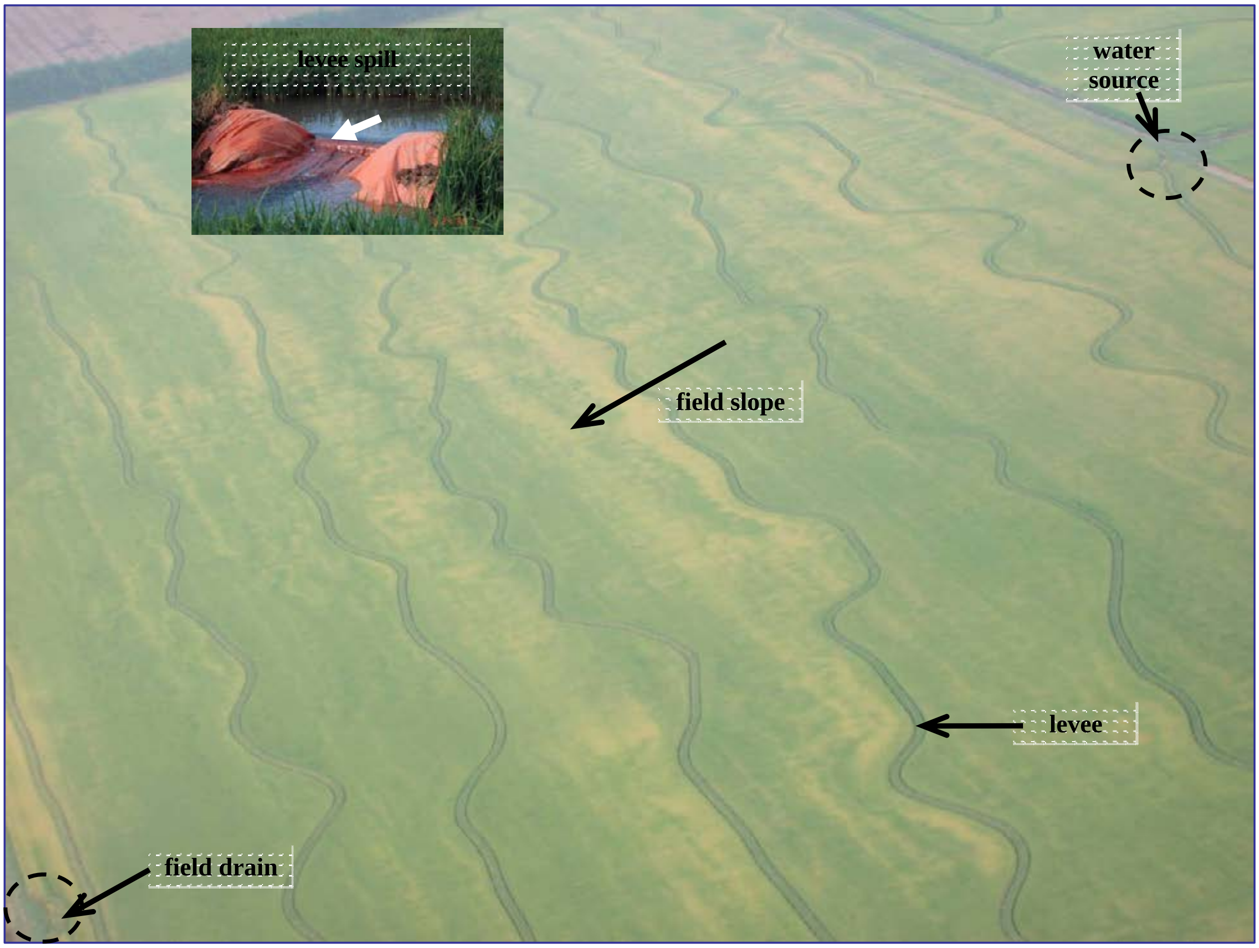


Figure 1. Aerial view of typical rice field in midsouthern US. Gates or spills are placed in the levees to allow water to flow from top to bottom of field.

Insufficient pumping results in dry portions of the fields, leading to increased weed and fertilizer problems and low yields. Excessive pumping wastes water and energy and increases pressure on levees. In addition, soil, fertilizers, and pesticides may be carried in the runoff from agricultural fields. It is essential that production practices be developed and refined that decrease the amount of irrigation water required while simultaneously protecting water quality. With increasing costs for energy and fertilizer, the solutions cannot be prohibitively expensive or they will not be adopted.

Flood depth affects most aspects of flooded rice production. Nutrient availability is highly affected by water management (Seng et al., 2004; Beyrouty et al., 1994), as is rice water weevil (Stout et al., 2002) and weed control (Masson et al., 2001). Therefore, rice producers commit much time, labor, and energy checking the water status of fields. As farms have grown to thousands of acres spread over several miles, remote monitoring of flood depth could be quite valuable to many producers.

Smith et al. (2007) looked at water use for different rice production systems in Mississippi and Arkansas and observed large differences. Vories et al. (2005) reported the results from four years of on-farm comparisons in Arkansas, showing 24% less irrigation water applied to multiple inlet rice irrigation fields compared to conventionally flooded fields without reducing yields. Massey et al. (2006) reported potential for additional water savings with multiple inlet plus intermittent irrigation. Intermittent irrigation allows the water levels to fluctuate more than with the conventional practice, which increases rainfall-holding capacity, and reduces over-pumping. Whatever system is used, the producer must have accurate information concerning the water status of each of the paddies in the field.

A company in Arkansas (Izon, Inc., Paragould, Ark.[5]) markets a system to notify producers when their well status changes (i.e., flow starts or ceases) or fuel levels are low. FieldSENTRY (Lindsay Manufacturing Co., Lindsay, Neb.) is a similar type of system for remotely monitoring center pivots. A similar type of system could monitor the depth of water in rice paddies and report to the grower when it is time to add water or stop pumping, reducing trips to the field just to check water status. The objective of this research is to develop and test a system for monitoring water depths in rice fields and alerting the producer so that less labor and energy is required to efficiently manage flood-irrigated rice.

PROCEDURES

Inexpensive sensors and wireless technology have advanced to the point that water status in rice fields could be remotely sensed and relayed to the producer at an affordable cost. With such a system (Figure 2), individual monitoring stations would be placed in each paddy; each station would measure the water depth and relay the information to adjacent stations. A central control station would collect the data from each paddy and send status reports to the producer.

Prototype Monitoring Station

A prototype monitoring station was designed to measure water depth in a flooded rice field. The system consists of a pressure sensor and microcontroller circuit housed in a waterproof container. The container is installed in the rice field so that a port in the side of the container is below the water level, allowing the pressure sensor to contact and measure the depth of water in the field (Figure 3). The monitoring station contains circuitry and components for measuring and recording pressure-sensor information at regular intervals, and for transmitting the information over a wireless link.

Table 1 lists the major components used in the prototype station. An inexpensive piezoelectric pressure sensor is used to measure the hydrostatic pressure of the water, which is a function of depth. A circuit was designed to monitor, store, and transmit pressure-sensor measurements. The circuit consists of a programmable microcontroller, real-time clock, memory chip, components to

[5] Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

power the pressure sensor and amplify the resulting sensor signal, and a radio-frequency (RF) transmitter. The components are inexpensive and commonly available items. A photograph of the prototype sensor components is included in Figure 4. The programmable microcontroller manages the control, logic, measurement, and data storage and transmission functions. The circuit is battery-powered, and capable of continuous, unattended operation for an entire growing season.

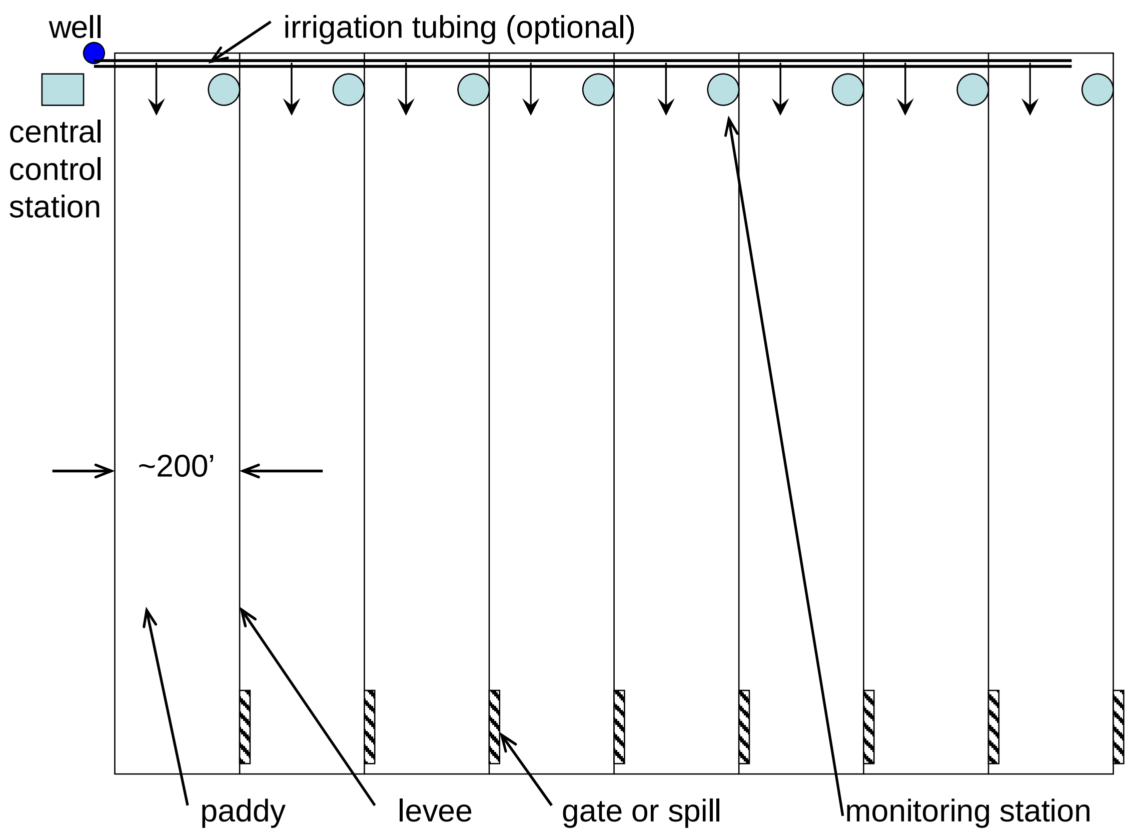


Figure 2. Diagram of monitoring system in rice field.

The microcontroller continuously monitors the real-time clock, which maintains time and date information, and maintains the circuitry in a low-power mode until it is time to take a measurement. At the beginning of each hour, the microcontroller activates the circuitry, turning on power to the other components. A depth measurement is made by providing power to the pressure sensor and measuring the output voltage signal. An operational amplifier is configured as a constant-current source, which powers the pressure sensor. The output voltage signal is input to an instrumentation amplifier, which increases the voltage level. The signal is then input to an analog-to-digital (A-D) converter built into the microcontroller, which measures the signal. The temperature of the pressure sensor is measured with an adjacent temperature sensor inside the PVC container for use in compensating for temperature effects on the pressure sensor. A calibration equation programmed into the microcontroller then calculates the water depth based on the pressure-sensor output voltage signal and the sensor temperature. Data are stored in a non-volatile memory chip and transmitted via a wireless transmitter. At each measurement interval, date and time, water depth, and temperature information are stored. This information, along with an identification number unique for each circuit board (i.e., monitoring station), is transmitted via the RF transmitter. The microcontroller then returns the circuit to low-power mode until the next measurement interval.

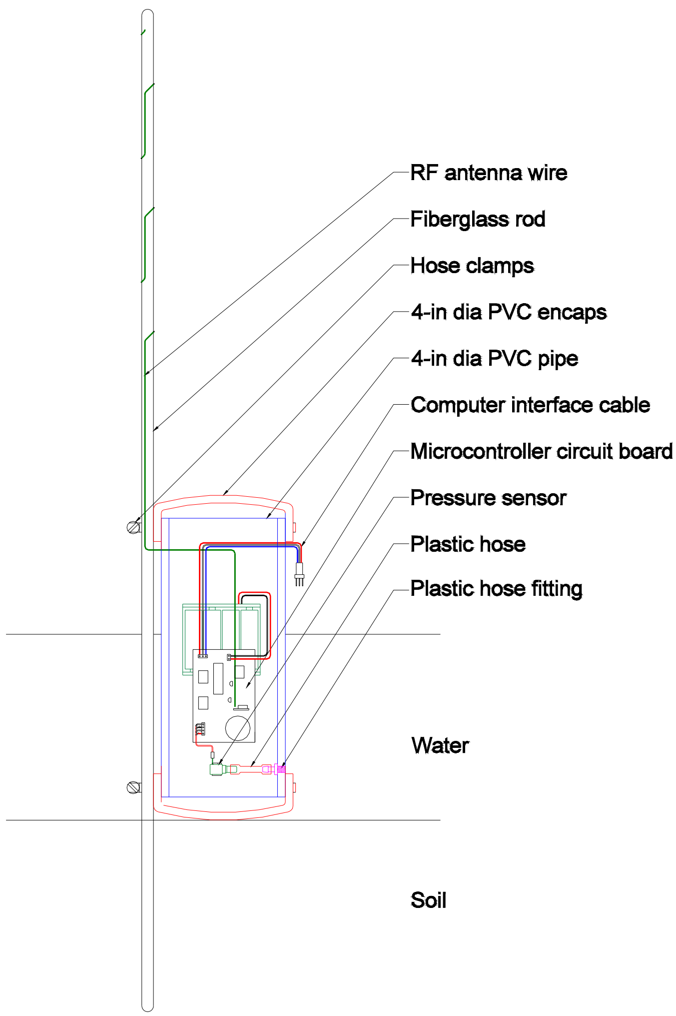


Figure 3. Sketch of monitoring station.

The waterproof container is constructed mainly of common PVC pipe and fittings. The bottom endcap is glued to one end of a short length of pipe. A small hole is drilled and tapped through the pipe wall just above the top lip of the endcap. A plastic hose barb is inserted and glued into the hole so that the barb extends into the inside of the pipe. A short length of plastic tubing is secured to the barb to allow attachment of the pressure sensor. A second hole is drilled through the pipe near the top of the container to allow the antenna wire and a computer-interface cable to pass through. A second endcap is placed on top of the pipe to secure and protect the electronic components. A fiberglass rod is used to install and secure the container in the field. The rod is driven into the soil, and the container is attached to the rod with hose clamps. The container is positioned on the rod so that the pressure sensor port is below the water surface at all times. The rod is also used to secure the antenna wire for the RF transmitter.

Table 1. Major components used in the prototype monitoring station circuit.

Component	**Manufacturer**
Microcontroller	Microchip Technologies
Pressure sensor	Honeywell
Real-time clock	Dallas Semiconductor
Memory	Microchip Technologies
Voltage regulator	Linear
Current source	Linear
Instrumentation amplifier	Analog Devices
RF transmitter	Laipac
Clock crystal	Seiko

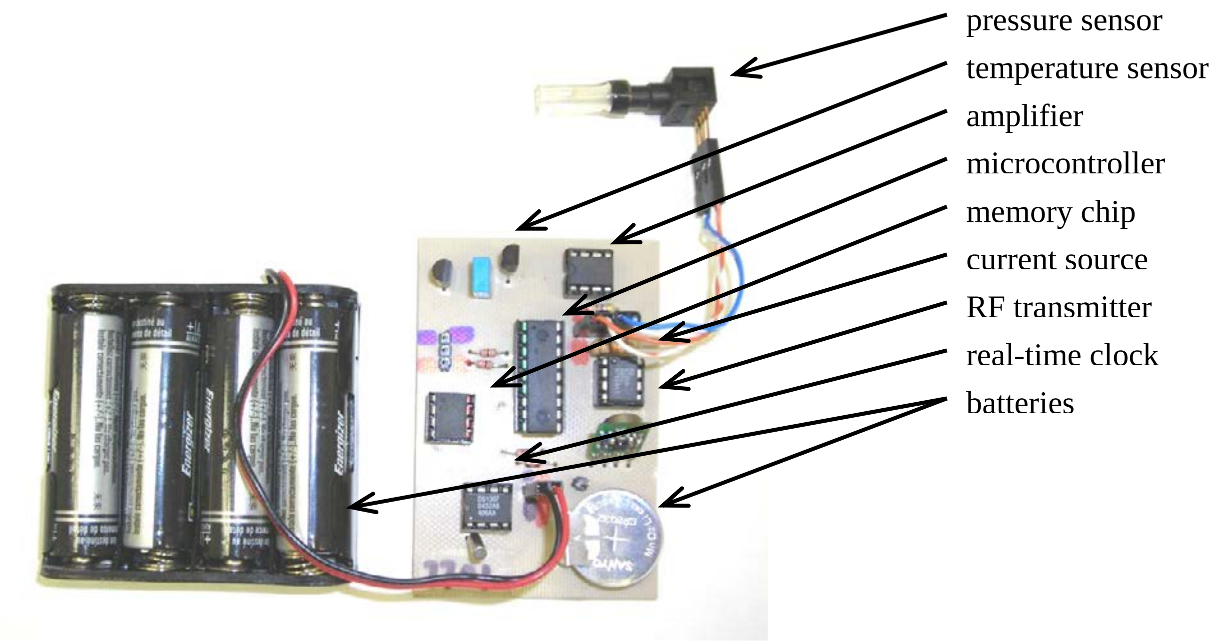


Figure 4. Photograph of prototype monitoring station components.

A similar sensor and circuit were installed in a raingage in 2006. Figure 5 shows a series of water-depth measurements from the raingage for a 10-day period in July. Automated measurements were taken at one-hour intervals, with periodic manual measurements of the water depth for comparison. A rain event occurred during which the raingage registered 0.61 inches of rainfall, compared with 0.63 inches from the “official” experiment station value.

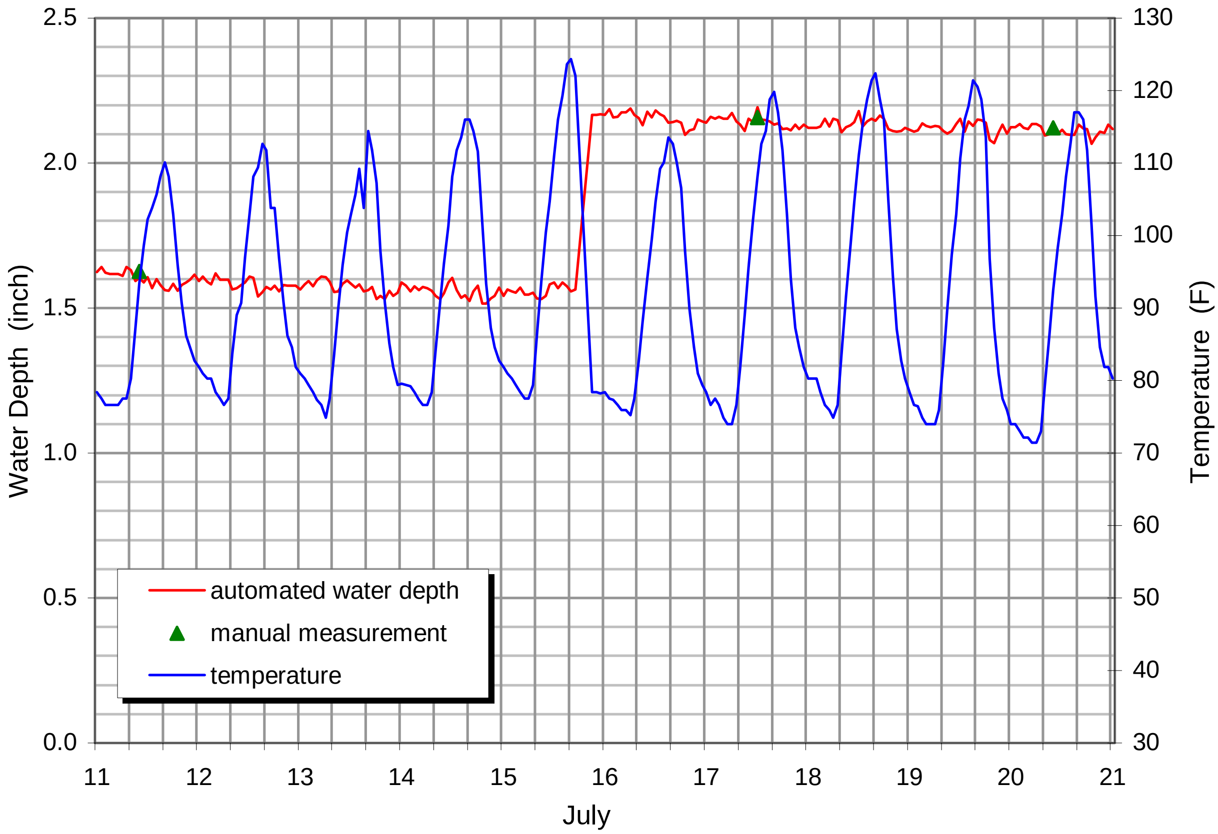


Figure 5. Graph showing a series of water-depth measurements from a raingage with a sensor and circuit similar to the prototype monitoring station.

System Testing

Initial tests conducted during summer 2007 will address the suitability of the inexpensive sensors under agricultural environments. Prototype monitoring stations (Figure 3) will be fabricated and installed in each paddy of two production rice fields (a target of at least ten stations). Logging flowmeters (McCrometer MD-308 with pulse output) and a logging tailwater depth sensor (INW PT2X, 5psig) will be installed in each field. Periodic visits will be made to the fields for manual depth measurements. Records will be kept regarding sensor-system failure rate and causes. The research team will meet after the season to discuss the results and how to address the failures. In the cases of water or farm equipment damage, better methods of protecting the units will be developed. If the first pressure sensors are deemed unsuitable, a different type of sensor will be identified the following year. Concurrently with the sensor durability testing, tests will be conducted to determine the limits of the low-cost wireless communication system within production rice fields, to determine antenna requirements and maximum communication distances. Once reliable sensors have been identified and communication requirements determined, additional complete systems will be assembled for field testing. Communication from the field to the producer (and researchers) will probably use an existing system (e.g., Izon, Inc.). The system will send daily status reports and additional alerts by text message and/or email when problems are suspected. Follow-up efforts will use the findings from the field testing to make inferences concerning potential water/energy/labor savings with the systems.

Potential Value

To get an idea of the potential value of a remote monitoring system, the situation of one northeast Arkansas producer was considered. The producer had 24 rice fields in 2006 for a total of 2,000 acres of rice (in this case, adjacent fields were counted as one since they would be visited at the same time). Each field was visited every day, and the average distance from the farm headquarters to the fields was approximately 10 miles. Typically on a large rice farm, one reliable, experienced worker, a "water man," is assigned to be in charge of maintaining the floodwater on all of the rice fields and during the approximately 70-day flood duration, that worker has little time for any other duties. With daily reports of the water status in each paddy, the field visits should be easily reduced to every third day, allowing the "water man" time for other work. In addition to the labor cost, significant savings should result from fuel costs spent driving to the fields and vehicle maintenance. Over-pumping should be reduced by allowing the worker to better schedule his visits to stop the pump, and future systems should work with the pump control system to automatically stop the pump before runoff occurred. Furthermore, by knowing the water status at all times, the producer would be more comfortable with intermittent irrigation (Massey et al., 2006) or some other approach that allowed more efficient use of rain.

SUMMARY

Insufficient pumping in rice production results in dry portions of the fields, leading to increased weed and fertilizer problems and low yields. Excessive pumping wastes water and energy and increases pressure on levees. In addition, soil, fertilizers, and pesticides may be carried in the runoff from agricultural fields. Flood depth affects most aspects of flooded rice production, including nutrient availability, rice water weevil, and weed control. Therefore, rice producers commit much time, labor, and energy checking the water status of fields. As farms have grown to thousands of acres spread over several miles, remote monitoring of flood depth could be quite valuable to many producers.

A prototype monitoring station was designed to measure water depth in a flooded rice field using an inexpensive piezoelectric pressure sensor, and transmit the information over a wireless link. A similar sensor and circuit were installed in a raingage in 2006 and performed satisfactorily. Initial efforts in summer 2007 will test the suitability of the inexpensive sensors under agricultural environments. Prototype monitoring stations will be fabricated and installed in each paddy of two production rice fields. Periodic visits will be made to the fields for manual depth measurements. Concurrently with sensor durability testing, tests will be conducted to determine the limits of the low-cost wireless communication system within production rice fields. Once reliable sensors have been identified and communication requirements determined, additional complete systems will be assembled for field testing. Follow-up efforts will use the findings from the field testing to make inferences concerning potential water/energy/labor savings with the systems.

Typically on a large rice farm, one worker is assigned to be in charge of maintaining the floodwater on all of the rice fields and that worker has little time for any other duties. With daily reports of the water status in each paddy, field visits should be easily reduced from daily to every third day, allowing the "water man" time for other work. In addition to the labor cost, significant savings should result from fuel costs spent driving to the fields and vehicle maintenance. Over-pumping should be reduced, and future systems should work with the pump control system to automatically stop the pump before runoff occurs. Furthermore, by knowing the water status at all times, the producer would be more comfortable employing an approach that allowed more efficient use of rain.

REFERENCES

Beyrouty, C. A., B. C. Grigg, R. J. Norman, and B.R. Wells. 1994. Nutrient uptake by rice in response to water management. J. Plant Nutr. 17(1):39-55.

Counce, P. A., T. C. Keisling, and A. J. Mitchell. 2000. A uniform, objective and adaptive system for expressing rice development. Crop Sci. 40(2):436-443.

Hogan, R., S. Stiles, P. Tacker, E. Vories, and K. J. Bryant. 2007. Estimating irrigation costs. FSA28-PD-6-07RV. Univ. of Ark. Coop. Ext. Serv. Little Rock, Ark.

Massey, J. H., M. C. Smith, A. Johnson, J. Thomas, P. L. Tacker, E. D. Vories, S. Lancaster, A. A. Andrews, and P. Ampim. 2006. Multiple-inlet plus intermittent rice irrigation increases rainfall capture and reduces non-point source runoff. Proc. Proc. 31st Rice Tech. Working Group:135. (CD-ROM)

Masson, J. A., E. P. Webster, and B. J. Williams. 2001. Flood depth, application timing, and imazethapyr activity in imidazolinone-tolerant rice (Oryza sativa). Weed Technol. 15(2):315-319.

NASS. 2005. Quick Stats: Agricultural Statistics Data Base. Available at: http://www.nass.usda.gov/QuickStats/. Accessed 8/30/2005.

Seng, V., R. W. Bell, and I. R. Willett. 2004. Amelioration of growth reduction of lowland rice caused by a temporary loss of soil-water saturation. Plant and Soil. 265(1-2):1-16.

Smith, M. C., J. H. Massey, J. Branson, J. W. Epting, D. Pennington, P. L. Tacker, J. Thomas, E. D. Vories, and C. Wilson. 2007. Water use estimates for various rice production systems in Mississippi and Arkansas. Irrig. Sci. 25(2):141-147. Available at: http://dx.doi.org/10.1007/s00271-006-0041-0.

Stout, M. J., M. R. Riggio, L. Zou, and R. Roberts. 2002. Flooding influences ovipositional and feeding behavior of the rice water weevil (Coleoptera: Curculionidae). J. Econ. Entomol. 95(4):715-721.

Vories, E. D., P. L. Tacker, C. Wilson, S. Runsick, and J. Branson. 2006. Water use measurements from the Arkansas rice research verification program. Proc. 31st Rice Tech. Working Group:136. (CD-ROM)

Vories, E. D., P. L. Tacker, and R. Hogan. 2005. Multiple inlet approach to reduce water requirements for rice production. Applied Eng. in Agric. 21(4):611-616.

VARIABILITY OF CROP COEFFICIENTS IN SPACE AND TIME — EXAMPLES FROM CALIFORNIA

Byron Clark[1]
Richard Soppe[2]
Deepak Lal[1]
Bryan Thoreson[1]
Wim Bastiaanssen[2,3]
Grant Davids[1]

ABSTRACT

Crop coefficients are calculated for almonds, citrus, and grapes in California based on a combination of remote sensing of actual crop evapotranspiration from the Surface Energy Balance Algorithm for Land (SEBAL®) and ground-based reference evapotranspiration from the California Irrigation Management Information System (CIMIS). Crop coefficients are calculated at the field scale, and the apparent variability in crop coefficients among fields and over time is examined. Crop coefficients derived from remote sensing are compared to published values used with reference evapotranspiration for estimation of crop water use. The opportunity to refine crop coefficients for irrigation management and water resources planning through improved understanding of the variability in crop water use via remotely sensed crop evapotranspiration estimates is discussed.

BACKGROUND

Increasing demand on limited fresh water supplies to satisfy multiple demands necessitates improved water management at all levels. Competition for fresh water supplies will continue to increase due to population growth, environmental requirements, and climate change. Improved tools are needed to quantify water use and enable planning that maximizes water use efficiency.

The consumptive use of water by crops (evapotranspiration, or ET) represents a major component of total water use in California. The California Department of Water Resources (DWR) estimates that in a typical year, 41% of the developed water supply is applied to agricultural lands. Of the water applied for irrigation, approximately 69% is consumed as crop ET. (DWR 2005a)

Crop water use is predicted to estimate water needs by water managers at field, farm, district, and regional scales. Because crop ET represents approximately two-thirds of the total water needed for irrigation, inaccuracies in predicted ET can have a substantial impact on projected water needs. Further, resource planners often estimate crop ET retroactively. Water balances ranging from small areas within irrigation districts to the entire State are performed to quantify flow paths such as consumptive use, surface runoff, and deep percolation. Based on the results,

[1] SEBAL North America, 1772 Picasso Avenue, Suite E, Davis, CA 95618, www.sebal.us.
[2] WaterWatch, Generaal Foulkesweg 28A, 6703 BS Wageningen, The Netherlands, www.waterwatch.nl.
[3] Delft Technical University, Stevinweg 1, Delft, The Netherlands, www.tudelft.nl

water management evaluations are made, and opportunities to increase water use efficiency through improved management are identified. Accurate characterization of actual crop ET is needed to accurately estimate water balance components and potential improvements to water use efficiency. Relatively small uncertainties in crop ET can translate into large uncertainties in other, lesser water balance components such as deep percolation.

THEORY

ET Estimation methods: K_c x ET_o

Crop ET is estimated from a variety of methods at multiple spatial and temporal scales. Among the most common ET estimation procedures employed by water managers is the K_c x ET_o approach, in which crop ET (ET_c) is estimated as the product of a crop and time specific crop coefficient (K_c) with consumptive use by a grass reference crop estimated for the period of interest using weather observations (reference ET, ET_o). Additionally, a stress coefficient, K_s, may be introduced to account for the effects of moisture or other stresses ($ET_c = K_c \times K_s \times ET_o$). Procedures for applying the K_c x ET_o approach have been documented extensively. Examples include Doorenbos and Pruitt (1977), Snyder et al. (1989), Jensen et al. (1990), and Allen et al. (1998).

In California, ET_o estimates are provided by the California Irrigation Management Information System (CIMIS). The CIMIS program began in 1982 and has established a state-wide network of more than 120 weather stations. For each weather station hourly, daily, and monthly ET_o estimates are available. CIMIS ET_o values are calculated using a modified version of the Penman equation as described by Pruitt and Doorenbos (1977). The CIMIS Penman additionally employs a wind function developed at the UC Davis (DWR 2005b). Calculations are performed on an hourly time step, and hourly values are summed to provide daily ET_o estimates.

Crop coefficients for use with CIMIS ET_o are available from a variety of sources including those listed above. Additionally, researchers, farm advisors, irrigation consultants, and growers have developed crop coefficients specific to their crops and fields based on observation of their specific field conditions.

Advantages of the K_c x ET_o approach include continuous water use estimates across time (typically hourly or daily time steps), estimates of ET for virtually any crop and stage of growth, and relatively lesser cost for small areas (e.g., a single farm or field). Disadvantages include inability to estimate ET variability within or among fields of the same crop in an area without detailed information describing actual field conditions, large uncertainty in the accuracy of crop coefficients, and relatively greater cost for detailed application to large areas.

ET Estimation Methods: Remote Sensing Energy Balance

Conservation of energy at the Earth's surface denotes a balance between net radiation reaching the Earth's surface from the Sun with combined soil, sensible, and latent heat fluxes. Latent heat flux (energy per unit area per unit time) can be easily converted into ET flux (volume of water per unit area per unit time) based on the latent heat of vaporization and density of water. ET flux can be estimated as a closure term from estimates of the remaining fluxes (Equation 1).

$$ET_a = \frac{1}{\lambda \rho_w}\left[R_n - (G + H)\right] \qquad [1]$$

where λ is the latent heat of vaporization of water, ρ_w is the density of water, ET_a is the actual crop ET, Rn is the net radiation flux at the Earth's surface, G is the soil heat flux, and H is the sensible heat flux.

<u>Description of SEBAL.</u> The SEBAL model applies radiative, aerodynamic, and energy balance physics in a series of 25 computational steps to estimate actual crop ET (ET_a) from the energy balance. ET_a is calculated at the pixel-scale using multispectral satellite imagery with a thermal band. The key input data consist of radiances in the visible, near infrared, and thermal infrared regions sensed by earth observing satellites; ground based weather data from agricultural or other weather stations; and land use data describing general vegetation types, when available. Knowledge of specific crop types is not needed to solve the energy balance. SEBAL is internally calibrated for each image to estimate sensible heat flux between the surface and the atmosphere, avoiding the need for absolute calibration of the surface temperature of each pixel. A detailed explanation of the algorithm is provided by Bastiaanssen et al. (1998).

<u>Validation of SEBAL.</u> SEBAL has been developed through 19 years of research and validation. Validation is ongoing as a means of quality control due to periodic refinements, sensitivity of model results to analyst judgments related to internal calibration, and interest in further quantifying the accuracy of the approach. The algorithm has been applied on more than 150 projects in 15 countries, including 19 projects in the United States (seven in California). Comparisons have been made to six different ET estimation methods for a variety of landscapes including irrigated pasture, sugar beets, riparian vegetation, playas, olives, rice, palm trees, cotton, wheat, sunflower, bare soil, grassland and forest. Seasonal ET_a estimates from SEBAL (multiple satellite images processed and integrated over time) compare well to seasonal ET_a from ground based measurements, falling within 5%. The deviation of ET_a values from ground-based measurements for shorter periods (instantaneous and up to 10 days) may be as much as 15 to 20%. The validation of SEBAL is summarized in detail by Bastiaanssen et al. (2005).

<u>Recent SEBAL Validations in California.</u> In addition to the numerous validation studies conducted world-wide, two validations have recently been conducted in California. Comparisons of SEBAL ET_a to ground-based estimates were conducted by Cassel (2006) for peaches, almonds, and alfalfa in the Southern San Joaquin Valley. It was found that SEBAL ET_a values fell within 5% of lysimeter and neutron probe estimates across a series of images processed for the 2002 growing season (April – October). Additionally, SEBAL estimates of district-wide ET_a for the Imperial Irrigation District were compared to an independent water balance (Soppe et al. 2006). Annual ET_a was calculated for the 1998 water year (October 1997 – September 1998) based on measured inflows and outflows. Total consumptive use from SEBAL was found to agree with the annual water balance within 1%.

Advantages and Disadvantages. Advantages of remotely sensed ET include the ability to estimate ET_a for any crop and stage of growth, ability to evaluate the variability within and among fields of similar types, ability to incorporate all environmental stresses into the ET estimate, ability to estimate ET across large landscapes using a single set of calculations for each image, and relatively low cost for large areas (e.g. a watershed or basin). Disadvantages include limitations in the frequency of ET estimates determined by the return interval of the satellite and relatively greater cost for estimating ET for small areas (e.g. a single farm or field).

Remote Sensing ET_a with Ground-Based ET_o to Estimate Crop Coefficients

The combination of continuous weather monitoring with periodic but spatially rich estimates of ET_a provides the opportunity to refine crop ET estimates by quantifying and explaining the spatial variability in crop coefficients. Once the variability in crop coefficients is spatially mapped, it is possible to examine factors that contribute to variability such as crop age, soil types, soil or water salinity, irrigation methods, shallow groundwater levels, or other spatial aspects of the irrigated landscape.

Tasumi et al. (2005) applied the surface energy balance algorithm METRIC™ to examine the variation in crop coefficients within crop populations for eight crops in Idaho. METRIC was developed based on SEBAL and modified for use specifically in Idaho and the Western U.S. (Tasumi et al. 2000, 2003; Allen et al. 2002, 2003). Field-scale crop coefficients were calculated and used to estimate relationships with the Normalized Difference Vegetation Index (NDVI), which provides an index of green vegetation. Additionally, crop coefficients from the energy balance were compared to standard values used for the K_c x ET_o approach.

METHODS

Three general data sources were utilized in this study. Existing SEBAL datasets providing ET_a estimates at the pixel scale derived from Landsat imagery were compiled. Cropped fields were identified using cropping data from DWR land use surveys and Kern County. ET_o was estimated from reported CIMIS values.

Field-scale crop coefficients were calculated for each image date. Existing SEBAL datasets and cropping data were compiled for each region. Field boundaries were buffered inward to identify areas in which ET_a estimates were not affected by heat transfer processes occurring outside of the field (thermal contamination). Then, ET_a and NDVI for each pixel within each field of interest were averaged to estimate field-scale ET_a and NDVI. Field values were filtered to remove fields with low NDVI during critical growth periods and to group fields based on estimates of fractional ground cover. Finally, field crop coefficients were calculated based on ET_o values from nearby CIMIS weather stations.

SEBAL Datasets

Three existing SEBAL datasets from California were selected as summarized in Table 1. The extent of each analysis area is shown in Figure 1.

Crop Classification

Land use data were obtained for each of three growing areas within the Landsat coverage areas of Figure 1. For the Southern San Joaquin Valley, almond, grape, and orange fields were identified based on 2002 cropping data provided by Kern County GIS (www.co.kern.ca.us/gis). For the Sacramento Valley, almond fields were identified based on 1998 and 2003 crop surveys for Colusa County and for 1998 and 2004 crop surveys for Sutter County from the DWR Division of Planning and Local Assistance (www.dpla2.water.ca.gov). For the Coachella Valley, citrus and grape fields were identified based on a combination of draft 2003 DWR cropping data (NRCS 2006) and 1996 digital orthoquad imagery from the California Spatial Information Library (CASIL, at gis.ca.gov).

Table 1. SEBAL Datasets Used for Crop Coefficient Analysis

Region	Satellite Platform	Row/ Path	Thermal Resolution[1]	Image Dates	Images
Southern San Joaquin Valley (2002 season)	Landsat 7 ETM	42/35	60 m	4/12, 5/14, 6/15, 7/17, 8/2, 9/3, 10/5/2002	7
Sacramento Valley (2001 season)	Landsat 7 ETM	44/33	60 m	4/23, 5/25, 6/10, 7/12, 7/28, 8/13, 8/29, 9/14/01	8
Colorado River (1998 season)	Landsat 5 TM	39/37	120 m	10/26, 11/27, 12/13/97; 1/14, 3/3, 4/4, 5/22, 7/9, 8/26, 9/27/98	10

1. 30 m resolution for visible and near infrared bands.

Figure 1. Landsat Scene Extents for SEBAL Analysis.

Buffering of Field Boundaries

Field boundaries were buffered inward to identify cropped areas that were not affected by thermal contamination. Thermal contamination of within field pixels occurs when lower resolution thermal pixels cross the field boundary and are affected by heat transfer processes outside of the field. For such pixels, the thermal radiance represents a weighted average of the radiance of the pixel area outside the field with the radiance of the pixel area inside the field.

Minimum buffering distances were estimated based on the pixel resolutions of the Landsat thermal band relative to the SEBAL outputs (30 meters). Based on the assumption that fields are generally rectangular in shape and oriented similarly to the Landsat pixels, a minimum inner buffer distance of 45 meters was estimated for Landsat 7, and an inner buffer distance of 105 meters was estimated for Landsat 5-based SEBAL outputs (Figure 2) The buffer distance was estimated so that only pixels containing a thermal pixel that was fully within the field boundaries are used. The buffer distances are somewhat conservative because the influence of heat transfer process occurring outside of the field increases as the thermal pixel area outside of the field increases.

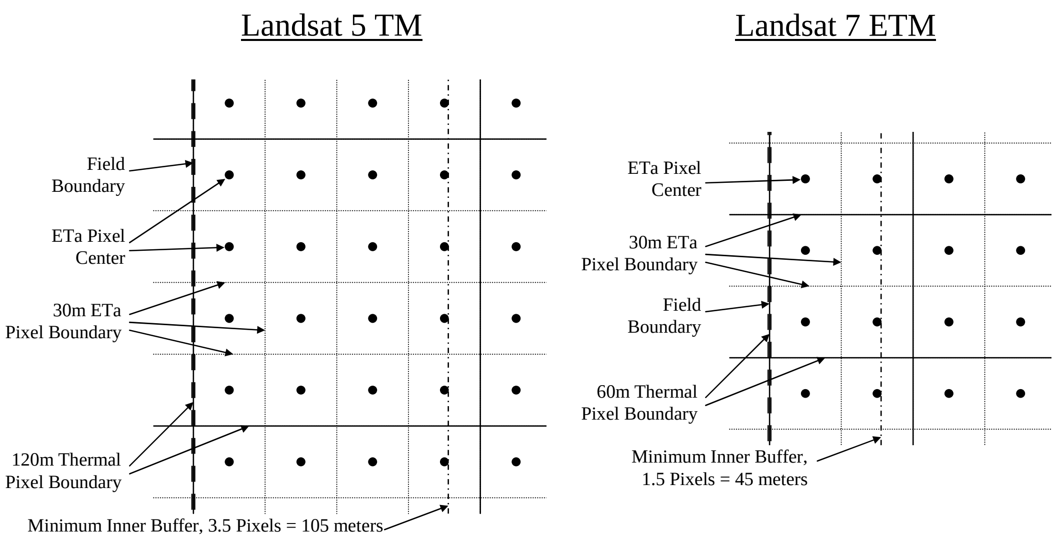


Figure 2. Inner Buffer Distance for Landsat Derived SEBAL Outputs

ET_a and NDVI values for each pixel within the buffered areas were extracted for each image and imported to a Microsoft Access database for calculation of field averages.

Filtering of Field Data Based on NDVI

Field ET_a values were filtered prior to the calculation of crop coefficients based on NDVI. Filters were applied in order to remove fields from analysis for which the land use data may be incorrect or the crop was poorly developed.

Threshold NDVI values for the filters were estimated based on a relationship estimating fractional canopy cover from NDVI (Equation 2) after the form of Choudhury et al. (1994):

$$f_c = 1 - \left(\frac{0.8 - NDVI}{0.8 - 0.125} \right)^{0.7} \qquad [2]$$

Threshold NDVI values corresponding to 10 percent incremental changes in fractional cover (f_c) were derived from Equation 2 and are given in Table 2. In addition to applying filters to remove suspect fields from analysis, fields for tree and vine crops were separated into fractional cover classes based on NDVI. NDVI criteria applied to each crop-region combination are summarized in Table 3. These criteria were selected qualitatively based on estimates of when crops in a region would be at maximum cover.

NDVI values were converted to fractional cover estimates to provide insight into the effect of varying ground shading on crop ET. Growers may not have access to NDVI measurements for their fields during the irrigation season, but can easily estimate fractional cover based on measurements of tree or vine shading relative to the total field area per plant (row spacing x plant spacing). NDVI may vary for reasons other than fractional cover such as crop type or other factors.

Table 2. Threshold NDVI Values Corresponding to Estimated 10 Percent Fractional Cover Increments from Equation 2.

f_c	*NDVI*
0.20	0.310
0.30	0.395
0.40	0.475

f_c	*NDVI*
0.50	0.550
0.60	0.618
0.70	0.680

Table 3. NDVI Criteria to Delineate Crop Canopy Cover Classes and Filter Field Records.

Region	Crop	Critical Time Period	Fractional Cover Class	NDVI Range
San Joaquin Valley	Almonds	5/14/02	> 0.6	> 0.618
			0.5 - 0.6	0.550 - 0.618
			0.4 - 0.5	0.475 - 0.550
			0.3 - 0.4	0.395 - 0.475
	Citrus	6/15/02	> 0.5	> 0.550
			0.4 - 0.5	0.475 - 0.550
			0.3 - 0.4	0.395 - 0.475
	Grapes	6/15/02	> 0.7	> 0.680
			0.6 - 0.7	0.618 - 0.680
			0.5 - 0.6	0.550 - 0.618
			0.4 - 0.5	0.475 - 0.550
			0.3 - 0.4	0.395 - 0.475
Sacramento Valley	Almonds	7/12/01	>0.7	> 0.680
			0.6 - 0.7	0.618 - 0.680
			0.5 - 0.6	0.550 - 0.618
			0.4 - 0.5	0.475 - 0.550
Coachella Valley	Citrus	4/4/98	> 0.5	> 0.550
			0.4 - 0.5	0.475 - 0.550
			0.3 - 0.4	0.395 - 0.475
	Grapes	5/22/98	> 0.7	> 0.680
			0.6 - 0.7	0.618 - 0.680
			0.5 - 0.6	0.550 - 0.618

Reference Evapotranspiration

Daily ET_o estimates for each region were obtained from CIMIS (wwwcimis.water.ca.gov). For each region and crop of interest, a single ET_o was calculated for each image date based on the area-weighted average of nearby stations using Thiessen polygons. Selected stations are listed in Table 4.

Table 4. Selected CIMIS Stations.

Region	Station ID	Station Name	Latitude	Longitude	Elevation (ft)	Start Date	Status
Southern San Joaquin	21	Kettleman	35.869	-119.894	340	11/19/1982	Active
	54	Blackwells Corner	35.650	-119.958	705	10/19/1986	Active
	125	Arvin-Edison	35.206	-118.778	500	3/22/1995	Active
	138	Famoso	35.604	-119.213	415	4/9/1997	Active
	146	Belridge	35.505	-119.690	410	10/9/1998	Active
	182	Delano	35.833	-119.256	300	3/21/2002	Active
Sacramento Valley	27	Zamora	38.808	-121.908	50	12/5/1982	Ended 1/20/06
	30	Nicolaus	38.871	-121.545	32	1/3/1983	Active
	32	Colusa	39.226	-122.024	35	1/13/1983	Active
Coachella Valley	50	Thermal	33.646	-116.242	-30	7/22/1986	Ended 1/11/1999
	141	Mecca	33.538	-115.992	-180	5/5/1998	Active

For the Coachella Valley, data for station 141 were not available until after the first six image dates. For the first six image dates, only the ET_o values for station 50 were used. For the Sacramento Valley, data for stations 30 and 32 were not available for the final three image dates. ET_o values for these dates were estimated from station 27.

Calculation of K_{cs}

Lumped crop coefficients representing combined evaporation, transpiration, and the effects of stresses were calculated from ET_a and ET_o for each field according to Equation 3.

$$K_{cs} = \frac{ET_a}{ET_o} \quad [3]$$

where K_{cs} is the lumped crop coefficient combining soil surface evaporation, crop transpiration, and stresses (i.e., $K_{cs} = K_c \times K_s$), ET_a is the field average SEBAL ET_a, and ET_o is the average CIMIS ET_o. The notation "K_{cs}" has been defined as a means of differentiating between crop coefficients based on optimum growing conditions (K_c) and crop coefficients based on actual growing conditions (K_{cs}).

Comparison to Published Crop Coefficients

Calculated K_{cs} values were compared to crop coefficients published for use with CIMIS ET_o. Sources of published crop coefficients selected for comparison were Snyder et al. (1989) and Consoli et al. (2006).

RESULTS AND DISCUSSION

Citrus

Southern San Joaquin. Average ET_a for each image date for 117 orange fields in Kern County with estimated f_c greater than 0.3 are presented in Figure 3 along with CIMIS ET_o. The relative frequency distribution of ET_a for the 117 fields are shown vertically along the axis of each image date as a means of visualizing the variability in ET_a (and K_{cs}) similar to Tasumi et al. (2005).

Calculated K_{cs} values for estimated f_c classes are presented in Figure 4 along with published values from Snyder et al. and Consoli et al. "K_{cs} (0.5)" denotes fields with fractional cover greater than 0.5, "K_{cs} (0.4)" denotes fields with fractional cover from 0.4 to 0.5, and "K_{cs} (0.4)" denotes fields with fractional cover from 0.3 to 0.4. This naming convention for estimated f_c classes is used through the remainder of this paper. Summary statistics of ET_a and K_{cs} for each fractional cover class are presented in Table 5.

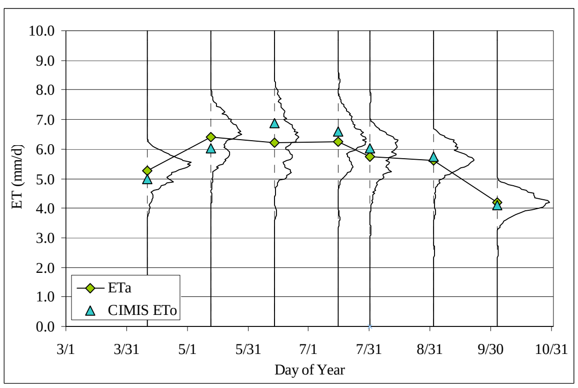


Figure 3. Kern County Orange ET_a and ET_o.

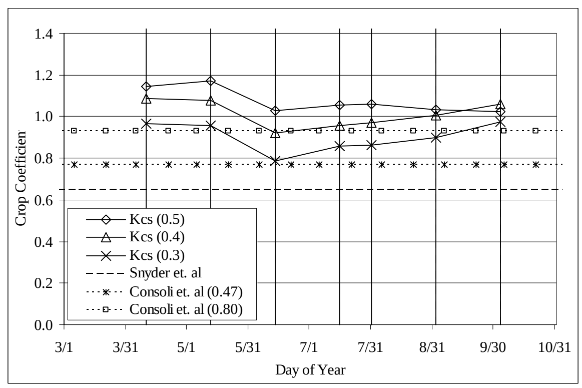


Figure 4. Kern County Orange Crop Coefficients from Remote Sensing, Snyder et al. (1989), and Consoli et al. (2006).

Orange ET was similar to reported ET_o throughout the images, with differences in ET_a (and K_{cs}) among fields explained, in part, by differences in NDVI. It is hypothesized that much of the variability in NDVI is due to differences in fractional cover, although the presence of cover crops or other factors could influence NDVI.

Calculated K_{cs} across the range of estimated f_c classes evaluated were generally greater than other reported values. Consoli et al. evaluated crop coefficients in navel orange orchards near Lindsay, California in the Southern San Joaquin Valley and found seasonal average K_{cs} values of 0.77 and 0.93 for fractional cover of 0.47 and 0.80, respectively. Higher crop coefficients estimated in this study may be due to underestimation of ET_o, limitations of the assumed f_c(NDVI) relationship, or inaccuracies in the ET_a estimates. K_{cs} values greater than those reported by Snyder et al. are consistent with the findings of Consoli et al. Variability in calculated K_{cs} across image dates is not unexpected due to uncertainties in ET_a values for individual images, however the average seasonal K_{cs} is expected to be within 5% of the actual value, provided that the ET_o values are accurate.

Table 5. ET_a and K_{cs} Summary Statistics for Kern County Oranges.

Fractional Cover Class	Number of Fields	Parameter	Statistic	Image Date						
				4/12/02	5/14/02	6/15/02	7/17/02	8/2/02	9/3/02	10/5/02
> 0.5	34	ET_a (mm/d)	Mean	5.70	7.04	7.09	6.96	6.33	5.95	4.27
			Std. Dev.	0.20	0.32	0.47	0.47	0.39	0.47	0.26
		K_{cs}	Mean	1.15	1.17	1.03	1.05	1.06	1.03	1.02
			Std. Dev.	0.04	0.05	0.07	0.07	0.07	0.08	0.06
0.4 - 0.5	40	ET_a (mm/d)	Mean	5.41	6.54	6.30	6.30	5.87	5.75	4.28
			Std. Dev.	0.17	0.24	0.38	0.33	0.33	0.30	0.28
		K_{cs}	Mean	1.09	1.08	0.92	0.96	0.97	1.01	1.06
			Std. Dev.	0.03	0.04	0.06	0.05	0.05	0.05	0.07
0.3 - 0.4	43	ET_a (mm/d)	Mean	4.81	5.76	5.42	5.67	5.19	5.19	4.03
			Std. Dev.	0.36	0.44	0.56	0.76	0.61	0.57	0.37
		K_{cs}	Mean	0.97	0.96	0.79	0.86	0.86	0.90	0.98
			Std. Dev.	0.07	0.07	0.08	0.12	0.10	0.10	0.09

Coachella Valley. Average ET_a for 107 citrus fields in the Coachella Valley with estimated f_c greater than 0.3 are presented in Figure 5 along with CIMIS ET_o. Estimated K_{cs} values for f_c classes and from Snyder et al. are presented in Figure 6. Summary statistics of ET_a and K_{cs} for each fractional cover class are presented in Table 6.

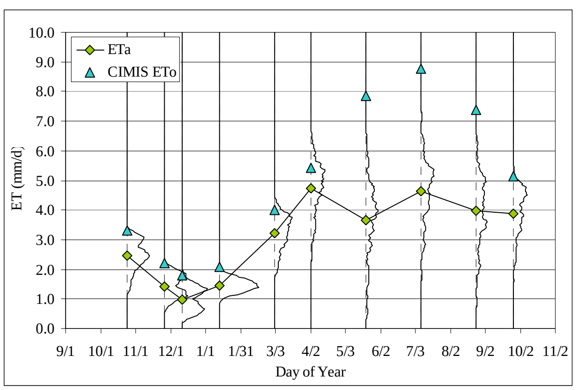


Figure 5. Coachella Valley Citrus ET_a and ET_o.

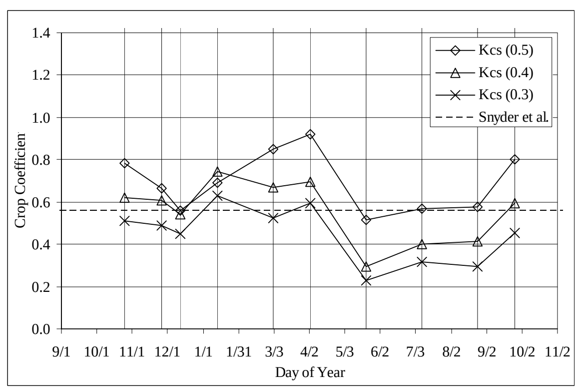


Figure 6. Coachella Valley Citrus Crop Coefficients from Remote Sensing and Snyder et al. (1989).

Estimated daily ET_a fell approximately 1 mm less than ET_o from late fall to March. Then, ET_o rose due to increasing evaporative demands. Despite the dramatic rise in ET_o from April through July, ET_a values appear to remain relatively constant. Steady ET_a values and decreases in K_{cs} for the summer months may be due to overprediction of ET_o or due to stresses related to weather conditions, salinity, and possibly moisture. Variation in K_{cs} among groups of fields classified based on NDVI is likely due to differences in fractional ground cover. Across the season, calculated K_{cs} values agree relatively closely to those reported by Snyder et al.

Table 6. ET_a and K_{cs} Summary Statistics for Coachella Valley Citrus.

Fractional Cover Class	Number of Fields	Parameter	Statistic	Image Date 10/26/97	11/27/97	12/13/97	1/14/98	3/3/98	4/4/98	5/22/98	7/9/98	8/26/98	9/27/98
> 0.5	85	ET_a (mm/d)	Mean	2.61	1.47	1.01	1.44	3.40	5.00	4.05	4.97	4.31	4.14
			Std. Dev.	0.38	0.37	0.40	0.20	0.45	0.65	0.96	0.74	0.87	0.64
		K_{cs}	Mean	0.79	0.67	0.56	0.69	0.85	0.92	0.52	0.57	0.58	0.80
			Std. Dev.	0.11	0.17	0.22	0.10	0.11	0.12	0.12	0.08	0.12	0.12
0.4 - 0.5	16	ET_a (mm/d)	Mean	2.07	1.34	0.97	1.55	2.68	3.79	2.31	3.53	2.98	3.05
			Std. Dev.	0.37	0.34	0.34	0.16	0.44	0.58	1.16	0.60	0.94	0.62
		K_{cs}	Mean	0.62	0.61	0.54	0.74	0.67	0.70	0.29	0.40	0.41	0.59
			Std. Dev.	0.11	0.16	0.19	0.08	0.11	0.11	0.15	0.07	0.13	0.12
0.3 - 0.4	6	ET_a (mm/d)	Mean	1.70	1.08	0.81	1.31	2.10	3.22	1.79	2.79	2.12	2.31
			Std. Dev.	0.29	0.17	0.12	0.20	0.44	0.61	1.09	0.56	0.87	0.67
		K_{cs}	Mean	0.51	0.49	0.45	0.63	0.52	0.59	0.23	0.32	0.29	0.45
			Std. Dev.	0.09	0.08	0.07	0.09	0.11	0.11	0.14	0.06	0.12	0.13

Comparison Among Regions. Crop coefficients for citrus trees with estimated f_c greater than 0.5 differed substantially between the San Joaquin and Coachella Valley regions. These differences may be due to differing environmental conditions (e.g., weather and soil conditions), production practices (e.g., irrigation methods and cover cropping), and differences between varieties grown. In general, the K_{cs} values for the Coachella Valley region appear substantially lesser and more variable with time than values from Kern County.

Almonds

Southern San Joaquin. Average ET_a values for 653 fields in Kern County with estimated f_c greater than 0.3 are presented in Figure 7 along with CIMIS ET_o. Estimated K_{cs} values for each f_c class are presented in Figure 8. Summary statistics of ET_a and K_{cs} are presented in Table 7.

Almond ET_a was similar to reported ET_o across the image dates, with differences in ET_a (and K_{cs}) among fields explained in part by differences in NDVI.

Interestingly, the 112 fields in the 0.3 – 0.4 estimated fractional cover class were found to have substantially lower K_c values than classes with higher NDVI. This may be due in part to the prevalence of drip rather than microsprinkler irrigation on recently planted orchards, which reduces the wetted soil surface area subject to evaporation. The majority of fields evaluated were found to have K_{cs} values at mid and late season (June – September) within the range of values suggested by Snyder et al. for orchards with and without a cover crop. Cover crops are likely present in some orchards, which would result in NDVI values representative of the combined tree and cover crop vegetation.

Similar to the results for citrus, relatively greater K_{cs} values were calculated for the first two image dates and for the final image date. Greater K_{cs} values early in the season may be due to a number of factors including presence of a cover crop early but not late in the season, presence of greater soil moisture early and late in the season leading to greater soil surface evaporation, greater transpiration early in the season prior to the onset of stress, inaccuracies in ET_o estimates early or late in the season, and inaccuracies in ET_a estimates for early and late season images.

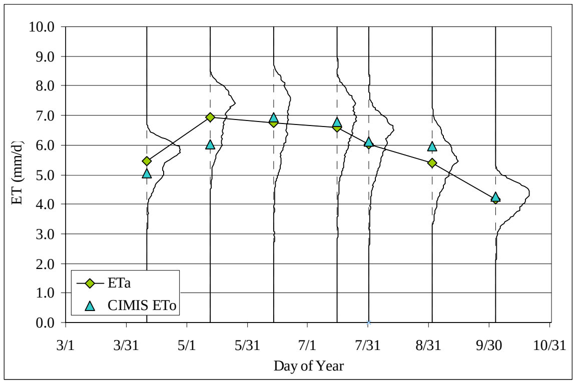


Figure 7. Kern County Almond ET_a and CIMIS ET_o.

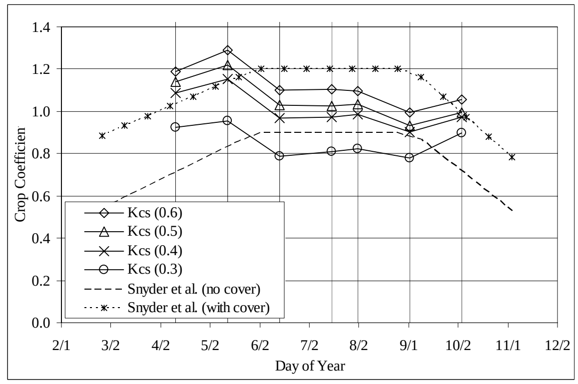


Figure 8. Kern County Almond Crop Coefficients from Remote Sensing and Snyder et al. (1989).

Table 7. ET_a and K_{cs} Summary Statistics for Kern County Almonds.

Fractional Cover Class	Number of Fields	Parameter	Statistic	Image Date 4/12/02	5/14/02	6/15/02	7/17/02	8/2/02	9/3/02	10/5/02
> 0.6	138	ET_a (mm/d)	Mean	5.96	7.77	7.63	7.43	6.68	5.86	4.42
			Std. Dev.	0.39	0.26	0.73	0.49	0.56	0.61	0.39
		K_{cs}	Mean	1.19	1.29	1.10	1.11	1.10	1.00	1.06
			Std. Dev.	0.08	0.04	0.11	0.07	0.09	0.10	0.09
0.5 - 0.6	219	ET_a (mm/d)	Mean	5.72	7.32	7.16	6.91	6.29	5.54	4.25
			Std. Dev.	0.32	0.33	0.62	0.57	0.50	0.57	0.39
		K_{cs}	Mean	1.14	1.22	1.03	1.03	1.03	0.93	0.99
			Std. Dev.	0.06	0.06	0.09	0.09	0.08	0.10	0.09
0.4 - 0.5	184	ET_a (mm/d)	Mean	5.25	6.56	6.33	6.21	5.74	5.18	4.01
			Std. Dev.	0.48	0.43	0.70	0.67	0.66	0.59	0.43
		K_{cs}	Mean	1.04	1.09	0.91	0.92	0.94	0.87	0.94
			Std. Dev.	0.09	0.07	0.10	0.10	0.11	0.10	0.10
0.3 - 0.4	112	ET_a (mm/d)	Mean	4.72	5.80	5.53	5.65	5.24	4.83	3.86
			Std. Dev.	0.48	0.47	0.84	0.89	0.83	0.71	0.43
		K_{cs}	Mean	0.92	0.96	0.79	0.81	0.82	0.78	0.90
			Std. Dev.	0.09	0.08	0.12	0.13	0.13	0.11	0.10

Sacramento Valley. Average ET_a values for 616 almond fields in the Sacramento Valley with estimated f_c greater than 0.4 are presented in Figure 9 along with CIMIS ET_o. Estimated K_{cs} values for each f_c class are presented in Figure 10. Summary statistics of ET_a and K_{cs} are presented in Table 8.

ET_a tracked closely with CIMIS ET_o for 4 of 8 image dates with ET_o exceeding ET_a in May, late July, late August, and September. Deviations for the May and late July images may be due to inaccuracies in reported ET_o, inaccuracies in ET_a, or possibly other factors. Decreases in ET_a relative to ET_o late in the season may be due to drying of the soil for harvest and the onset of dormancy and senescence.

Midseason K_{cs} values for fields with estimated f_c from 0.5 to 0.6 agree closely to the values provided by Snyder et al. for orchards without cover crops. K_{cs} values for fields with greater NDVI approach the values reported for fields with cover crops. Relatively greater K_{cs} values for the April image may be due to soil surface evaporation or the presence of a cover crop. Lesser K_{cs} values during September and October may be due to deficit irrigation practices prior to harvest or to an earlier end to the season for the Sacramento Valley than estimated based on the published values.

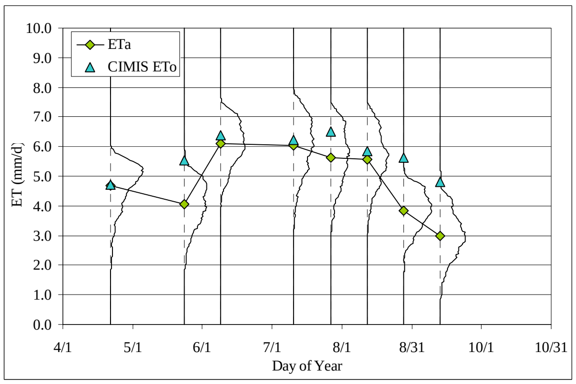


Figure 9. Sac Valley Almond ET_a and CIMIS ET_o.

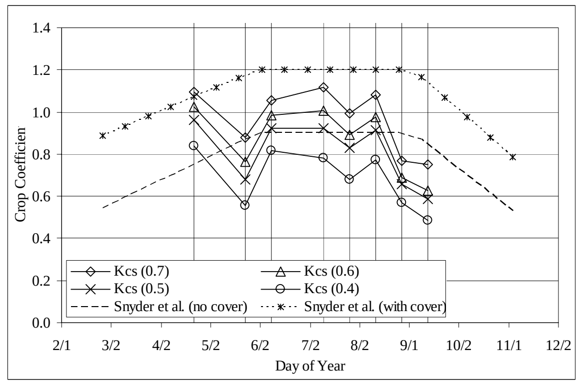


Figure 10. Sac Valley Almond Crop Coefficients from Remote Sensing and Snyder et al. (1989).

Table 8. ET_a and K_{cs} Summary Statistics for Sacramento Valley Almonds.

Fractional Cover Class	Number of Fields	Parameter	Statistic	Image Date 4/23/01	5/25/01	6/10/01	7/12/01	7/28/01	8/13/01	8/29/01	9/14/01
> 0.7	184	ET_a (mm/d)	Mean	5.19	4.77	6.78	6.99	6.58	6.40	4.33	3.62
			Std. Dev.	0.51	0.44	0.41	0.33	0.50	0.69	0.48	0.66
		K_{cs}	Mean	1.10	0.88	1.06	1.12	0.99	1.08	0.77	0.75
			Std. Dev.	0.11	0.08	0.06	0.05	0.08	0.12	0.08	0.14
0.6 - 0.7	138	ET_a (mm/d)	Mean	4.84	4.24	6.28	6.27	5.80	5.69	3.89	3.01
			Std. Dev.	0.53	0.40	0.39	0.35	0.48	0.59	0.49	0.59
		K_{cs}	Mean	1.02	0.76	0.98	1.01	0.89	0.97	0.69	0.63
			Std. Dev.	0.11	0.07	0.06	0.06	0.07	0.10	0.09	0.12
0.5 - 0.6	167	ET_a (mm/d)	Mean	4.56	3.84	5.88	5.71	5.33	5.30	3.71	2.83
			Std. Dev.	0.57	0.43	0.43	0.40	0.53	0.57	0.43	0.50
		K_{cs}	Mean	0.96	0.68	0.92	0.92	0.83	0.91	0.66	0.59
			Std. Dev.	0.12	0.08	0.07	0.06	0.08	0.10	0.08	0.10
0.4 - 0.5	127	ET_a (mm/d)	Mean	3.97	3.12	5.21	4.84	4.40	4.51	3.20	2.33
			Std. Dev.	0.68	0.53	0.46	0.59	0.67	0.66	0.48	0.57
		K_{cs}	Mean	0.84	0.56	0.82	0.78	0.68	0.77	0.57	0.48
			Std. Dev.	0.14	0.09	0.07	0.09	0.10	0.11	0.08	0.12

Comparison Among Regions. Comparison of calculated K_{cs} values for almonds in the Sacramento and San Joaquin Valleys show similarities and differences. In each case, April K_{cs} values appear to be greater than midseason values. Midseason, K_{cs} values for fields with estimated cover from 0.5 to 0.6 are near 0.9 for the Sacramento Valley and near 1.0 for the San Joaquin. During September, calculated K_{cs} values for the Sacramento Valley declined to 0.6 while calculated San Joaquin K_{cs} values remain near 0.9.

Grapes

Southern San Joaquin. Average ET_a values for 352 grape fields in Kern County with estimated f_c greater than 0.3 are presented in Figure 11 along with CIMIS ET_o. Estimated K_{cs} values for each f_c class are presented in Figure 12. Summary statistics of ET_a and K_{cs} are presented in Table 9.

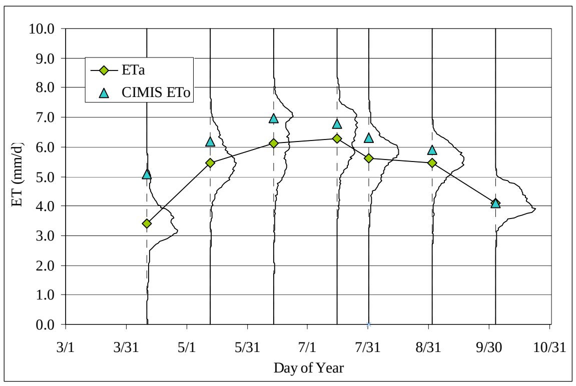


Figure 11. Kern County Grape ET_a and CIMIS ET_o.

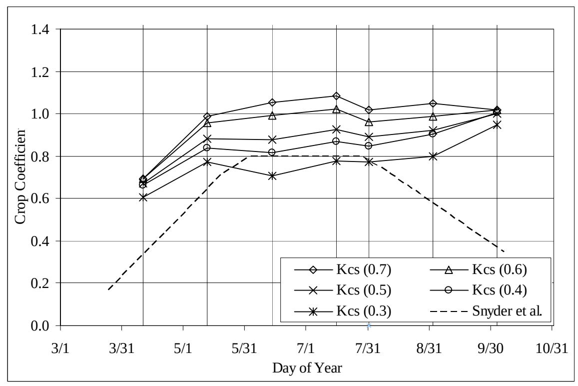


Figure 12. Kern County Grape Crop Coefficients. from Remote Sensing and Estimated from Snyder et al. (1989).

Calculated K_{cs} values for Kern County grapes were approximately 0.6 to 0.7 in early March and increased to 0.7 to 1.1 by midseason. Variation in K_{cs} among fields may be due to differences in f_c or other factors that influence NDVI. Late season K_{cs} values were not found to decrease as predicted based on reported values, possibly due to a longer crop season than estimated or due to soil evaporation late in the season.

Table 9. ET_a and K_{cs} Summary Statistics for Kern County Grapes.

Fractional Cover Class	Number of Fields	Parameter	Statistic	Image Date						
				4/12/02	5/14/02	6/15/02	7/17/02	8/2/02	9/3/02	10/5/02
> 0.7	43	ET_a (mm/d)	Mean	3.44	5.92	7.23	7.09	6.04	5.95	4.20
			Std. Dev.	0.53	0.42	0.31	0.31	0.31	0.34	0.35
		K_{cs}	Mean	0.69	0.99	1.05	1.08	1.02	1.05	1.02
			Std. Dev.	0.11	0.07	0.04	0.05	0.05	0.06	0.09
0.6 - 0.7	69	ET_a (mm/d)	Mean	3.48	5.86	6.89	6.86	5.96	5.76	4.21
			Std. Dev.	0.66	0.62	0.41	0.48	0.45	0.42	0.40
		K_{cs}	Mean	0.69	0.95	0.99	1.02	0.96	0.99	1.02
			Std. Dev.	0.13	0.10	0.06	0.07	0.07	0.07	0.10
0.5 - 0.6	77	ET_a (mm/d)	Mean	3.60	5.61	6.37	6.48	5.78	5.52	4.08
			Std. Dev.	0.57	0.58	0.50	0.56	0.45	0.40	0.36
		K_{cs}	Mean	0.72	0.91	0.92	0.97	0.92	0.95	1.01
			Std. Dev.	0.11	0.09	0.07	0.08	0.07	0.07	0.09
0.4 - 0.5	88	ET_a (mm/d)	Mean	3.38	5.23	5.71	5.91	5.43	5.37	4.12
			Std. Dev.	0.55	0.45	0.57	0.52	0.56	0.39	0.40
		K_{cs}	Mean	0.66	0.84	0.82	0.87	0.85	0.91	1.01
			Std. Dev.	0.11	0.07	0.08	0.08	0.09	0.07	0.10
0.3 - 0.4	75	ET_a (mm/d)	Mean	3.13	4.87	4.98	5.44	5.09	4.94	3.96
			Std. Dev.	0.93	0.73	0.86	0.78	0.68	0.63	0.40
		K_{cs}	Mean	0.60	0.77	0.71	0.78	0.77	0.80	0.95
			Std. Dev.	0.18	0.12	0.12	0.11	0.10	0.10	0.10

Coachella Valley. Average ET_a for 208 grape fields in the Coachella Valley with estimated f_c greater than 0.5 are presented in Figure 13 along with CIMIS ET_o. Estimated K_{cs} for each f_c are presented in Figure 14. Summary statistics of ET_a and K_{cs} are presented in Table 10.

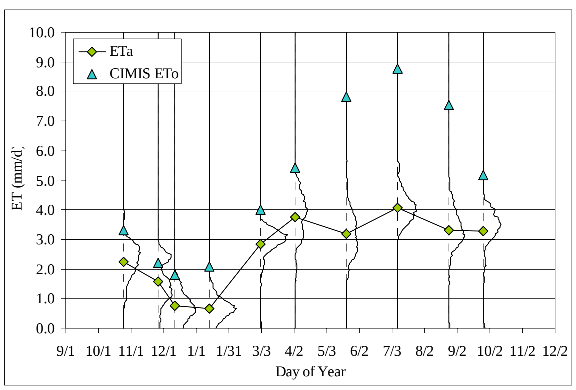


Figure 13. Coachella Valley Grape ET_a and CIMIS ET_o.

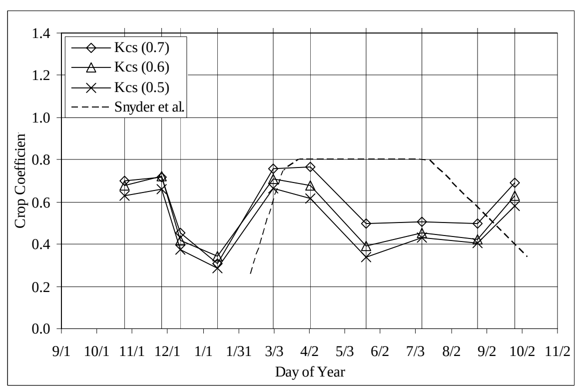


Figure 14. Coachella Valley Grape Crop Coefficients from Remote Sensing and Estimated from Snyder et al. (1989).

Table 10. ET_a and K_{cs} Summary Statistics for Coachella Valley Grapes.

Fractional Cover Class	Number of Fields	Parameter	Statistic	Image Date 10/26/97	11/27/97	12/13/97	1/14/98	3/3/98	4/4/98	5/22/98	7/9/98	8/26/98	9/27/98
> 0.7	54	ET_a (mm/d)	Mean	2.33	1.59	0.81	0.64	3.03	4.16	3.89	4.45	3.74	3.59
			Std. Dev.	0.43	0.65	0.44	0.30	0.47	0.68	0.71	0.50	0.74	0.60
		K_{cs}	Mean	0.70	0.72	0.45	0.31	0.76	0.76	0.50	0.51	0.50	0.69
			Std. Dev.	0.13	0.30	0.25	0.15	0.12	0.12	0.09	0.06	0.10	0.12
0.6 - 0.7	111	ET_a (mm/d)	Mean	2.25	1.60	0.75	0.72	2.84	3.70	3.07	3.98	3.19	3.26
			Std. Dev.	0.57	0.67	0.44	0.38	0.60	0.72	0.57	0.43	0.70	0.87
		K_{cs}	Mean	0.68	0.72	0.42	0.34	0.71	0.68	0.39	0.45	0.42	0.63
			Std. Dev.	0.17	0.30	0.24	0.18	0.15	0.13	0.07	0.05	0.09	0.17
0.5 - 0.6	43	ET_a (mm/d)	Mean	2.09	1.46	0.67	0.59	2.67	3.35	2.64	3.77	3.05	3.01
			Std. Dev.	0.56	0.67	0.43	0.28	0.49	0.83	0.55	0.37	0.59	0.74
		K_{cs}	Mean	0.63	0.66	0.37	0.28	0.67	0.62	0.34	0.43	0.40	0.58
			Std. Dev.	0.17	0.30	0.24	0.13	0.12	0.15	0.07	0.04	0.08	0.14

Calculated K_{cs} values at the end of the rapid development period (approximately March – April) were found to be similar to estimates from reported values, with differences due in part to variability in NDVI. Calculated K_{cs} values declined by late May and remained relatively constant through August, possibly due to overprediction of ET_o, deficit irrigation to control shoot growth following harvest (Coachella Valley grape harvest typically occurs from late May to early July), and due to environmental stresses. K_{cs} values were found to increase by late September and remained relatively constant through November, possibly due to overhead sprinkling of grapes to induce dormancy (a common practice in the Valley) and due to the presence of cover crops.

Comparison Among Regions. Calculated K_{cs} values for Kern County remained relatively constant through the summer months, while Coachella Valley K_{cs} decreased by late May. The decline in K_{cs} for the Coachella Valley region relative to Kern County may be due to differences in environmental factors such as weather conditions, soil characteristics, soil and water salinity, or due to differences in production practices such as deficit irrigation following harvest to control shoot growth.

Another factor that may explain differences in grape crop coefficients between the Coachella Valley and Kern County regions may be differences in production practices related to the end-product produced. In the Coachella Valley, grapes are produced exclusively for the fresh market, while in Kern County approximately 38% of grapes were grown for the fresh market, 35% were grown for wine, and 27% were grown for raisins during the study period (2002 Kern County Crop Report). Differences may include different trellis systems and resulting fractional cover differences as suggested by the relatively large number of Kern County fields with estimated f_c less than 0.5 (may be wine grapes, which often are grown on smaller trellises) when compared to the Coachella Valley, where the vast majority of the fields had cover greater than 0.5. Additionally, irrigation practices may differ (such as deficit irrigation to control wine grape quality), which may not affect fractional cover but does affect the ET flux.

CONCLUSIONS

Crop coefficients under actual field conditions vary substantially for individual crops within a region and across regions. Remote sensing of actual ET using high resolution satellite imagery allows for assessment of this variation. Impacts of field and region specific factors such as fractional cover, soils, weather conditions, irrigation and cultural practices, and salinity may explain these variations. Additional studies that incorporate spatial knowledge of these variables are needed to quantify their effect on crop water use under actual field conditions. Increased frequency of remotely sensed ET_a estimates as well as evaluation of K_{cs} values across more than a single growing season are needed to better define the variation in crop coefficients with time.

Crop coefficients estimated for this study were calculated based on reported ET_o values used for irrigation management. Future studies aimed at establishing standard K_{cs} values for general use must incorporate greater quality control to reduce uncertainties in ET_o for the remote sensing image dates. Additionally, ground based ET estimates using surface renewal or other techniques are needed to reduce inaccuracies in remotely sensed ET_a for individual image dates for K_c studies. The combination of remotely sensed ET_a with ground based estimates of ET_a and ET_o has the potential to increase the accuracy with which crop water use can be predicted at varying scales using the K_c x ET_o approach, enabling improved water management.

ACKNOWLEDGEMENTS

The authors wish to thank the California Department of Water Resources staff and researchers at the University of California for providing a wealth of valuable information describing ET_o, cropping patterns, and crop coefficients in California. Additionally, the provision of detailed cropping information for 2002 by Kern County GIS is greatly appreciated.

REFERENCES

Allen, R.G., Morse, A., and Tasumi, M. (2003). Application of SEBAL for Western US Water Rights Regulation and Planning. Proceedings of the ICID International Workshop on remote Sensing. Montpellier, France.

Allen, R.G., Morse, A., Tasumi, M., Trezza, R., Bastiaanssen, W.G.M., Wright, J.L., and Kramber, W. (2002). Evaptranspiration from a Satellite-Based Surface Energy Balance for the Snake River Plain Aquifer in Idaho. Proceedings of the USCID/EWRI Conference on Energy, Climate, Environment, and Water. San Luis Obispo, California.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop Evapotranspiration. Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nations. Rome, Italy.

Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., and Holtslag, A.A.M. (1998). A Remote Sensing Surface Energy Balance Algorithm for Land (SEBAL): 1. Formulation. Journal of Hydrology, 212-213: 198-212.

Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., and Allen, R.G. (2005). SEBAL Model with Remotely Sensed Data to Improve Water Resources Management Under Actual Field Conditions. Journal of Irrigation and Drainage Engineering. 131(1), 85-93.

California Department of Water Resources (DWR). (2005a). California Water Plan Update. Volume 3: Regional Reports. Sacramento, California

California Department of Water Resources (DWR). (2005b). Description of CIMIS PM Equation. wwwcimis.water.ca.gov/cimis/infoEToCimisEquation.jsp.

Cassel S., Florence. (2006). Final Report: Remote Sensing of Evapotranspiration for Verification of Regulated Deficit Irrigation. Project #04FG203069. United States Bureau of Reclamation.

Choudhury, B.J., Ahmed, N.U., Idso, S.B., Reginato, R.J., and Daughtry, C.S.T. (1994). Relations Between Evaporation Coefficients and Vegetation Indices Studied by Model Simulations. Remote Sensing of Environment. 50, 1-17.

Consoli, S., O'Connell, N., and Snyder, R. (2006). Estimation of Evapotranspiration of Different-Sized Navel-Orange Tree Orchards Using Energy Balance. Journal of Irrigation and Drainage Engineering. 132(1), 2-20.

Doorenbos, J. and Pruitt, W.O. (1977). Crop Water Requirements. Irrigation and Drainage Paper No. 24, Food and Agriculture Organization of the United Nations. Rome, Italy.

Jensen, M.E., Burman, R.D., and Allen, R.G. (ed.). (1990). Evapotranspiration and Irrigation Water Requirements. ASCE Manual and Report No. 70, American Society of Civil Engineers, New York, New York.

Natural Resources Conservation Service (NRCS). (2006). A Review of Agricultural Water Use in the Coachella Valley. Watershed Planning Services, Natural Resources Conservation Service, US Department of Agriculture. Davis, California.

Pruitt, W.O. and Doorenbos, J. (1977). Proceedings of the International Round Table Conference on Evapotranspiration. Budapest, Hungary.

Snyder, R.L., Lanini, B.J., Shaw, D.A., and Pruitt, W.O. (1989). Using Reference Evapotranspiration (ET_o) and Crop Coefficients to Estimate Crop Evapotranspiration (ET_c) for Trees and Vines. Leaflet No. 21428, Cooperative Extension, University of California. Berkeley, California.

Soppe, R.W., Bastiaanssen, W., Keller, A., Clark, B., Thoreson, B., Eckhardt, J., and Davids, G. (2006). Use of High Resolution Thermal Landsat Data to Estimate Evapotranspiration within the Imperial Irrigation District of Southern California. Oral Presentation. American Geophysical Union 2006 Fall Meeting. San Francisco, California.

Tasumi, M. (2003). Progress in Operational Estimation of Regional Evapotranspiration Using Satellite Imagery. PhD Dissertation, University of Idaho, Moscow, Idaho.

Tasumi, M., Allen, R.G., and Bastiaanssen, W.G.M. (2000). The Theoretical Basis of SEBAL. Idaho Department of Water Resources, Idaho. 46-69.

Tasumi, M., Allen, R.G., Trezza, R., and Wright, J.L. (2005). Satellite-Based Energy Balance to Assess Within-Population Variance of Crop Coefficient Curves. Journal of Irrigation and Drainage Engineering. 131(1), 94-108.

ASSESSING THE IMPLEMENTATION OF INTEGRATED WATER MANAGEMENT APPROACH IN CLOSED BASINS

Wael Khairy[1]

ABSTRACT

The National Water Resources Plan of Egypt launched in 2005 estimates that the New Lands would reach 45% of the agricultural land by 2017. The Plan envisions an increase of Egypt's agricultural land, over the period of 2000 to 2017, from 8.5 million acres to 11.2 million acres which is about 7.24% of Egypt area. The existing Oases of Egypt's Western Desert, considered part of the New Lands, form a small portion of the agricultural area. These lands are developed either by private reclamation entities or the Ministry of Water Resources and Irrigation through a varity of cooperative efforts including land and water grants to settlers, commercial farms, and providing services to the oases. The Government of Egypt has followed an efficient and sustainable path rooted based on the integrated water management approach in allocating substantive investments towards the development of the oases as anchors of the Western Desert New Land.

This study outlines a case study on the assessment of development and management aspects of water resources and land in closed basins. The case study focuses on the implementation of integrated water management approach in Siwa Oasis. This historic Oasis has been chosen as a model of water and land management in closed basin of Egypt's New Lands. In Siwa, integrated land and water management parallel with an enabling policy that fosters social and environmental sustainability have been practiced since the late nineties. This study has concluded positive consequences of applying integrated water management in various aspects of life in Siwa Oasis. Positive indicators show an increase in crop productivity, +40%; +25% growth of organized inhabitant settlement measured by family income and livelihood standards; and improving environmental quality by more that 50%.

INTRODUCTION

Egypt, being located in a belt of extreme aridity, is among countries that are very vulnerable with regard to water resources. The country depends mainly on the River Nile for its water supply (55.5 billion m^3 per year). Yearly average rainfall is approximately three millimeters that mostly with an obvious bias towards the north, Figure (1). The total effective rainfall used for drinking water and agriculture is about 1.3 billion cubic meters per year (Abdel-Gawad, et al., 2002). However, under these limited water resources conditions, population that exceeds 72 million capita, is increasing at a rate that might jump over 3% (Campos, 2006). The availability of other fresh water resources is very small (at present only about 3% of the demand) and possibilities to develop other resources within the country are limited. Being the most downstream country in the Nile basin, Egypt is very vulnerable for developments upstream and a basin-wide approach is

[1] Dr. Wael M. Khairy, Director, Minister's Office, Ministry of Water Resources and Irrigation, EGYPT. E-mail: waelk@mwri.gov.eg, Phone : +202 544 9420, Fax : +202 544 9470, Mailing Address: Cornaich El-Neel, Imbaba, Ministry of Water Resources and Irrigation, Postal Core 12666, Giza, EGYPT.

needed to safeguard Egypt's supply (Nile Basin Initiative 1989).

There are many-water related challenges facing Egypt. As the population continues to grow steadily and development efforts are intensifying in order to produce food and raise standards of living, it is expected that water demand will continue to increase. Traditional irrigation practices lead to loss of irrigation water that is not just wasteful; it can ruin the land through salinization, water-logging, and pollution and it means precious foreign exchange must be spent to import food. Another factor contributing to intensifying Egypt's water challenges is that environmental pollution is causing serious water quality deterioration, thus affecting public health and impairing the safe use of significant water.

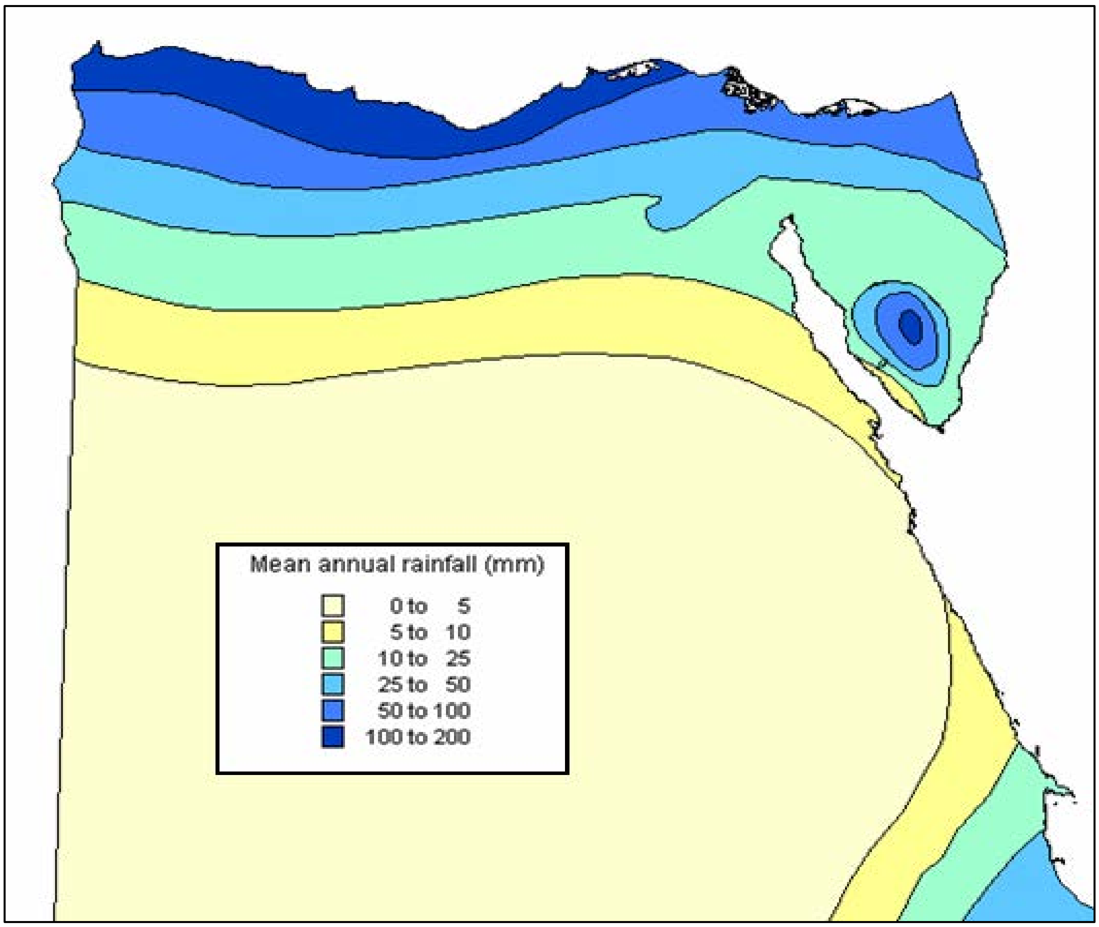


Figure 1. Rainfall distribution in Egypt

NATIONAL WATER RESOURCES PLAN OF EGYPT

In view of the serious water resources challenges that face Egypt, it is clear that the development of a long-term plan to improve irrigation practices for food production in Egypt represents a life-and-death urgency. A National Water Resources Plan (NWRP) was finalized and launched in 2005 by the Ministry of Water Resources and Irrigation (MWRI). The MWRI has taken the lead in developing the plan, but through involvement of the main stakeholders, the developed plan is

considered a real national plan (Bron, J., 2001 and Water Boards Project, 2002).
The objective of water resources development in Egypt is derived from the national development goals and policies (1998 ،بيومي عطية، وفاطمة عبدالرحمن). In general terms the national development goals related to water resources are,

- to increase the economic growth of the country and to increase employment;
- to increase the inhabited space of Egypt outside the Nile Valley and the Delta, by:
  - a) developing new cities
  - b) developing the Eastern Delta and Sinai (i.e., the El-Salam Canal)
  - c) developing the Western Desert and New Valley areas in Southern Egypt (i.e., Siwa Oasis, Toshka Project, and East Owenat)
- to protect public health by means of provision of safe drinking water and adequate sanitation facilities
- to protect the Nile and other fresh water resources from pollution.

The Plan describes how Egypt will safeguard its water resources in the future; both with respect to quality and quantity, and how it will best use these resources from socio-economic and environmental perspectives (Ministry of Water Resources and Irrigation, 2005). The plan is based on an Integrated Water Resources Management (IWRM) approach, taking into account the objectives of all water users, covering the period till the year 2017. MWRI developed policies and guidelines for water management in Egypt. These policies and guidelines are dynamic in nature to allow for changing conditions and the new NWRP provides an update of earlier policies and plans. It provides binding objectives, guidelines, and institutes for agencies working in Egypt’s water sector.

The NWRP recognizes that facing water-related challenges is a collaborative effort of all stakeholders. The stakeholders involved in implementation of the Plan include those who are actual water users such as the agricultural, industrial and drinking water and sanitation sectors and stakeholders who are concerned about water resources because of their mandates such as health and environmental protection sectors. Stakeholders' involvement is essential for better application of the policy activities (Advisory Panel Project, 2001). The participatory approach includes regular inter-sectoral consultations, stakeholder representation on certain water management bodies and coordination mechanisms. All stakeholders concerned have major responsibilities in the implementation of Egypt’s water policy. The NWRP is accompanied by implementation policies for all involved ministries and national organizations. The Plan assigns the expansion of Egypt’s agricultural land to the Ministry of Agriculture and Land Reclamation (MALR) and Ministry of Water Resources and Irrigation (MWRI). The successful completion of this task will expand the agricultural lands by 3.4 million feddans[1] (acres) by same target year 2017 (Abu Hidb and Fu’ad., 1992). Currently the agricultural lands of Egypt are about 8.0 million feddans (acres); however, about 40% of Egypt's food requirements is imported. The intention of NWRP is to guide both public and private actions in the future for ensuring optimum development and management of water that benefits both individuals and the society at large.

1 A Feddan is a common area measuring unit in Egypt, equals to ~ 4200 m^2 = 1.038 acre = 0.42 hectare

The Plan that was born to address Egypt’s growing population and economic development activities which have increased the pressure on the limited water resources and its infrastructures requires investments to better utilize and develop the available water resources and priority measures to safeguard those resources. At the same time institutional changes will be needed to decentralize and integrate the various activities. Developments in the legal and regulatory environment have to support these changes. Understanding these requirements and the importance of water resources for the socio-economic development of the country, the Government of Egypt (GOE) is committed to all necessary means and measures to manage and develop the water resources of the country in a comprehensive and equitable manner.

National Water Resources Plan of Egypt and International Commitments

From household and local scheme to regional and global water fora, water for development and water for food themes generated debate in 2003 and 2006 among the rich and poor, corporate and public sectors, and industrialized and developing countries (Abu-Zeid, 2003). Water was not only topical but also defined the sustainable development agenda during the years. It will remain a major issue in the decades to come, because water is life - for people and the environment. At the beginning of this century, world leaders declared their intention to work for a world in which people would be free from want and fear.

In this regard, Egypt, similar to other countries worldwide, has posted an impressive record with regard to the Millennium Development Goals (MDGs) targets. Currently, potable water supply coverage for urban and rural populations is very close to 100 percent and 95 percent, respectively. Per capita consumption has increased from 130 liters per day to 275 liters per day between 1981 and 2000. Sewerage and sanitation coverage also increased eightfold between 1982 and 2000, reaching about 70% and 25% in urban and rural areas (including Egyptian Oases), respectively. Wastewater treatment coverage increased from 6 percent to 30 percent. The Government is working hard toward eradication of poverty and improving living standards for all inhabitants in urban, rural, desert, and oases areas (Ministry of Planning of Egypt, 2005 and United Nation, 2002).

THE CASE STUDY

The Development Policy

The study area, Siwa Oasis, is part of the New Lands. Egypt's total arable and inhabitable area is only about 4% of its total area. The majority of its population of about 72 million inhabitants still concentrates in the narrow Nile Valley and the Delta, the so-called Old Lands. The Western Desert Region includes a number of oases; in particular, Siwa, Bahariya, and Farafra which are about 25% of Egypt’s total area. The high population density puts a heavy burden on Egypt's infrastructure and services, and causes massive migration to urban centers, especially Cairo and Alexandria, with consequent urban overcrowding. This explains why Egypt has "turned to its deserts" for expansion, despite the heavy costs involved and the impact on its limited water resources. The NWRP envisages that by 2017 the agricultural area will have grown from 7.8 to 11.2 million feddans. Of the current 7.8 million feddans, 6.2 million feddans consists of Old

Lands, and 1.6 million feddans of Old/New Lands and New Lands. This would mean that with the envisaged expansion of 3.4 million feddans (acres), Egypt's cropped land would consist for 45% of Old/New and New Lands by 2017 (NWRP, 2005).

Development in most of the desert lands only started in the late 1980s, except in the oases, which are much older. Typically these lands were developed by single purpose state owned reclamation agencies, the General Authority for Reconstruction Projects and Agricultural Development (GARPAD) and MWRI, which make land and water available to a mix of settlers, sell land to commercial farms and operate the services in the area.

The new desert reclamation policy aims primarily at developing sustainable communities in newly reclaimed areas. A major divergence from the prior policies is the private sector's dominant role in the new mega projects. While the government contribution in the early stages of these projects is significant, the long-term value added activities of the private sector approaches 75-80%. The government investment is limited to the construction of major infrastructures networks including roads, communications, and central power stations. In this respect the government has set up an investor-friendly regulatory environment for projects located in remote regions (Investment Law No. 8, 1997). Various vehicles for attracting foreign investors into the water resources sectors and the new frontiers of Egypt New Lands have been instituted by the government (American Chamber, 2005). Design, Build and Operate (DBO) projects are successful outcome of these new policies, e.g., the Irrigation Improvement Project in West Delta, a Public-Private Partnership (Project Appraisal Document, 2006); and the Toshka Project, part of New Land.

Description of the Study Area

The Western Desert Region includes a number of these oases; in particular, Siwa, Bahariya, and Farafra are about 25,000 hectares in total. The study area in this paper is Siwa Oasis, which situated in the middle of the western desert of Egypt, 26^{o} $40^{\backslash}$ to 27^{o} $40^{\backslash}$ latitude, 27^{o} $30^{\backslash}$ to 28^{o} $40^{\backslash}$ longitude. It is almost 20 m below msl. It is bounded from the north, east and south by escarpment of the surrounding desert plateaus, +270 m to +300 m MSL, with residual hills as high as +350, Figure 2. SIWA population was about 25,000 in year 2005 and the population variability rate is very low. It includes many antiquities sites since ancient Egyptians times. Siwa inhabitants have their special traditions and ways of life that have been preserved for centuries. The area is famous for its dates and olives production, and is one of the most beautiful landscapes in Egypt. Famous olives' oil continues to be made in the area by crushing the olives from the 70,000 olive trees with stones. The area is also famous for its 1,000 natural springs. The water is sweet, and is believed to have remedial benefits. Intra-governorates migration and resettling of inhabitants who gained good money after working abroad for some years continued toward SIWA. It has attracted a number of private companies and private reclamation entities and investors over the last two decades. As a result, various large and privately owned companies and Olives and Dates production business started randomly without consultation with the associated governmental agencies or local authorities.

Hydrogeology, Climate and Major Land Features

Rainfall is completely absent throughout the year in Siwa Oasis. The heaviest shower recorded during the last two decades did not exceed 3.5 mm. The only available water resources in the Oasis are the fossil groundwater from the Nubian Sandstone Aquifer. The area has a nice climate, chilly in winter, hot in the summer and moderate in the spring and autumn. Average temperature ranges from 25 to 37^{o}C and reaching 45^{o}C (absolute maximum) from time to time in summer. In winter, the temperature ranges from 17 to 25^{o}C, and drops to zero, especially late at night during January and February. Generally, temperature cools rapidly after sunset during both summer and winter. Other climate parameters vary as follows,

- Relative humidity ranges from 24 to 35%, and not exceeding 60% in winter.
- Evaporation ranges from 12 to 26 mm/day during summer and from 5 to 12 mm/day during winter.
- Wind speed ranges from 1.5 to 5 m/sec and characterized by heavy dust, especially during April till June as well as during September and October.

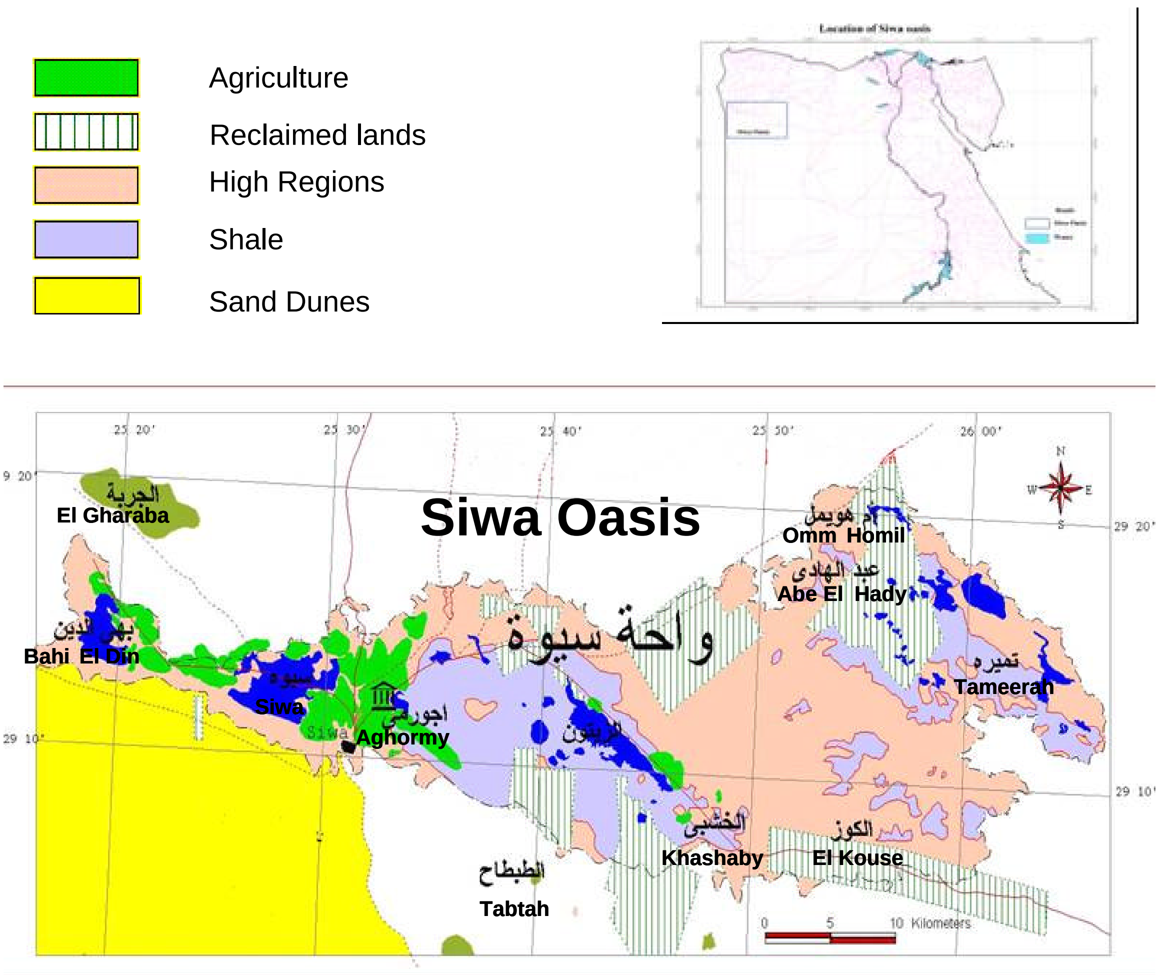


Figure 2: Siwa oasis layout showing its four main ponds

Although in terms of quantity the contribution of deep (fossil) groundwater to the total water supply in Egypt is very moderate, groundwater is the sole source of water for people living in the desert areas. There is increasing interest in further developing these groundwater resources. Present abstractions of deep groundwater are about 0.9 BCM/year, however, the potential is about 4.0 BCM/year. Figure (3) shows surface distribution of aquifer system and groundwater development status in Egypt.

Aquifer systems are distributed over the country (Figure 3). The Nubian Sandstone aquifer system is assigned to the Paleozoic-Mesozoic. It occupies a large area in the Western Desert, and parts of the Eastern Desert and Sinai. Groundwater can be found at very shallow depths, where the water bearing formation (horizon) is exposed; or at very large depths (up to 1,500 m), where the aquifer is (semi)confined. The deepest water bearing horizons are generally encountered in the north (Siwa); while the shallowest are encountered in the southern portion (East Uweinat and Kharga). The aquifer transmissivity is generally medium to low, varying from 1,000 to 4,000 m^2/day.

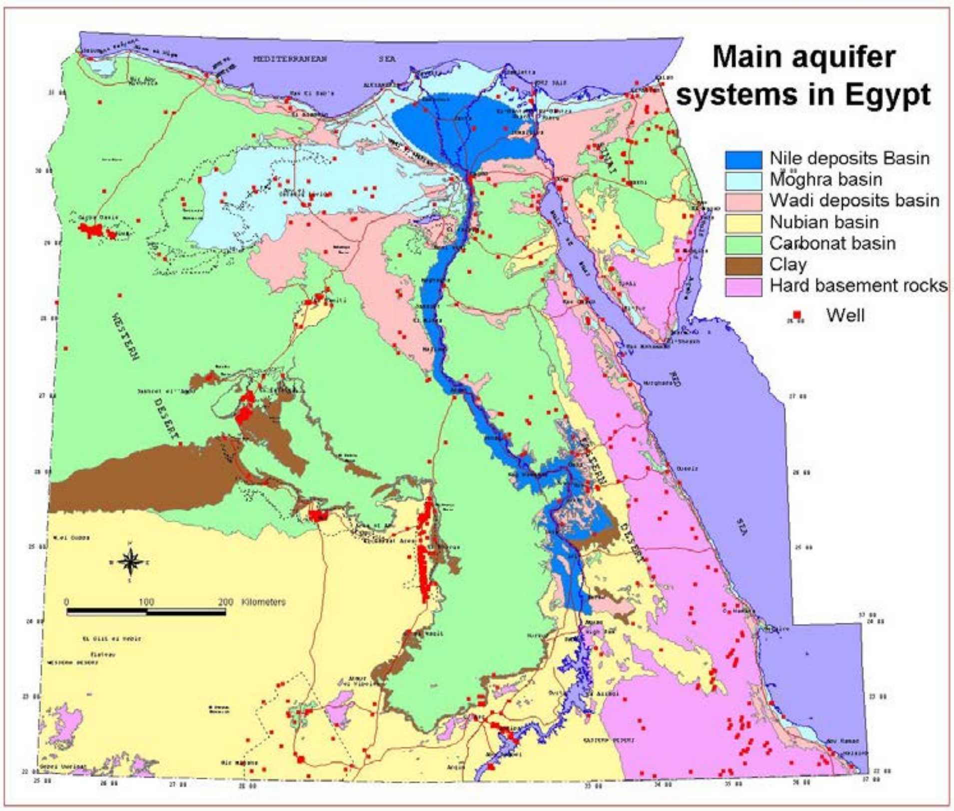


Figure 3. Surface distribution of aquifer systems and groundwater development areas in Egypt and Siwa Oasis

(Source: Groundwater Sector, Ministry of Water Resources and Irrigation, Egypt, 2006)

The Nubian sandstone aquifer system is a regional system. It extends into Libya, Sudan and Chad. The aquifer contains a huge amount of non-renewable groundwater dating back to the rainy period (25,000 to 40,000 years). Groundwater quality is generally good (<500 ppm) in the major part, except near the coastal regions and Sinai. Groundwater recharge is limited (estimated at 500 million m^3/year) across the boundaries with Chad and Sudan.

The dominated soil type is sandy silt with heavier clay soils in some locations. The eastern edge of the Great Sand Sea encroaches on the western margin of the greater Siwa depression.

Challenges of Water Resources Development in the Study Area

The majority of the population in the oases is low-income, average per capita annual income is below 400 U.S dollars. Those employed by the government and mostly the new inhabitants are immigrants from Nile Valley and Delta. Similarly, employees of private reclamation entities and investors are temporarily workers and immigrants. Thus, the new inhabitants formed rather heterogeneous ethnic and linguistic groups who exploited water resources in the Oasis without any planning which often lead to disputes and conflicts among the users. In addition, within Siwa Oasis, agriculture totally depends on the groundwater abstracted through deep wells from Nubian Sandstone aquifer, which is a finite resource.

The Oasis lacked a sanitary system up to the nineties. Health services are particularly poor in the area. Most of the rural clinics are operational with shortage of basic medical equipment. Schools, although evenly distributed in the secondary administration districts, are still very limited compared to other New Lands.

Unlike the Old Lands of the Nile Delta and Valley, the oases lands are characterized by a complicated geo-morphology and topography, which require specific land and water management approaches that were not recognized at the time of reclamation. Other constraints were mostly due to the remote location of the oases that is mostly caused by lack of communication, services, and transportation infrastructures and the required framework for development and management.

Agricultural practices in Siwa before late nineties was a typical case of mismanagement that was manifested by

- Increased population and inhabitants' activities;
- Developing of new lands and digging of new wells;
- Growth of agricultural lands by reclamation of low lands because of initial availability of water;
- Increasing number of wells in lower areas;
- Dry of wells in higher areas that lead to the use of pumping;
- Increase of drainage flows that exceed the sustainable potential of local groundwater;
- Rising groundwater table causing increase of soil salinity;
- Rising lake water level and increase in lake area and salinity;
- Water logging.

THE MITIGATION PLAN

MWRI has developed policies and tested practices for integrated development such as water and agricultural sectoral reform, decentralization, user participation and private sector mobilization. As a consequence of good land management, the adoption of the new policies in the oases is favorable. This encouraged the MWRI to pursue the broader aspects of development by mobilization of private capital to stakeholders including cooperatives, holding companies and publically owned companies

The MWRI started a rigorous integrated water resource management plan for sustainable development in late Nineties to mitigate the degraded situation in Siwa Oasis. It protects the areas from soil degradation and groundwater from over-pumping. Among the objectives of the plan are the following,

- Rehabilitate / initiate water supply infrastructure.
- Strengthen capacity of local communities to manage water and introduce participatory water management.
- Conduct awareness programs aiming at rationalizing water use and reducing losses.
- Urging inhabitants to enroll in water user associations on different levels such as; mesqas (farm irrigation ditches), tertiary canals, branch canals, etc.
- Develop marketing capacity and market oriented products.
- Increase agricultural production (per unit of supplied / consumed water) through improved / appropriate desert agriculture.
- Increase water-use efficiency and encourage transfer of development towards non-conventional ones (less water and lower water quality, including reuse) to ensure sustainability of communities.
- Diversify economic activities, making use of the comparative advantage of the Oasis.

Replacement of inefficient wells and enhancement of the irrigation and drainage networks in the study area have slowed down the wasteful pumping of groundwater which ended at drainage swamps. Though only a small portion of the irrigated agriculture is served by groundwater wells, these sources are of vital importance in those particular areas. The MWRI developed a system for user management for groundwater systems in the Oasis. In the absence of water management institutions by the MWRI in these areas, it would be necessary to establish a “District Water Board” in the Oasis thus reorganizing importance of local authorities’ institutions.

Parallel efforts taken by the Government to encourage large capital investments to stimulate economic growth included, introduction of value-added activities, agro-business, in the Dates and Olives manufacturing sector; development of specialty farms for export crops; expanding tourism programs serving antiquates sites in Siwa Oasis; and facilitating the commercial use of groundwater, e.g., bottled water packing plants. This implementation projects are still on-going by the MWRI aiming at restoring agricultural productivity, good livelihood standards, and clean environment in SWIA Oasis.

Native inhabitants, private reclamation entities and investors, and local authorities shared cooperation and progress with the Government for mitigating the problem. The survey done within this study found that before the implementation projects only 280 of a total of 1260 production wells had been controlled to save the unused groundwater. New wells, 142, had to be constructed to cover water shortage in some areas of the Oasis. These were built by local communities including beneficiaries, private reclamation entities, and investors). Currently, all groundwater companies in Siwa share a unified well constructed practice and follow a sustainable operation plan.

The Government of Egypt lead by MWRI has been carrying out large implementation projects in Siwa Oasis that included,

- Constructing controlled high capacity productive wells to replace the old randomly constructed wells, with cooperation of local communities.
- Constructing lined and elevated mesqas to replace natural narrow mesqas with high seepage.
- Rehabilitating old field drainage network.
- Constructing new open drainage canals.
- Cleaning weeds and maintaining cross-section areas of all waterways.
- Regulating water levels throughout the year at the four main swamps in Siwa.
- Providing agricultural and irrigation advisory services.
- Supporting local authorities to improve their institutional setup in water sector.
- Promoting and facilitating industries export (especially agro-industrial products such as olives and dates products), hand craft dresses and tools, and potable water industry.
- Encouraging establishment of Water Users Associations (WUAs) in Siwa.
- Attracting tourism toward the antiquity sites and health fitness sites in Siwa.

The success of the mitigation is evident through the rational use of the precious groundwater resources and improved environmental quality. These wouldn’t have been possible without the integrated approach of management that provides the badly needed technical know-how to the natives who are willing participants in the plan. This has lead to new areas ready for expansion at the different parts of the Oasis which are inhabited with the native habitants. Overall, water was provided for the expansion of cultivating in 30 thousand additional feddans (acres) in the Oasis.

METHODOLGY

Integrating Water Resources Management is an inclusive and sustainable approach that accounts for the multiple-use of water resources within an environment of laws and regulations based on societal values that govern the socioeconomic settings and driven by market forces. The multiple-use of water resources covers relevant areas such as hydropower, water supply and sanitation, irrigation and drainage, and commercial and industrial needs. An integrated water resources perspective ensures that a sustainable environmental quality considering social, economic, and technical dimensions are achieved and accounted in the management and development of water resources.

The analysis conducted through this study was limited to the problems faced by native communities in Siwa and may have resulted from reverse immigration toward the Oasis. Some survey results and indicators used in previous survey (محمد عبد المنعم شحاته وآخرون، 2004) were used as guidelines for this assessment.

Study Objectives

The objectives of this study were focused on assessing implementation outcome of integrated land and water management approach in "Closed Basins" with focus on Siwa Oasis and identifying institutional deficiencies in order to develop appropriate policy changes. Three measures for the assessment were used; these are standards of living measured by sustainable livelihood of communities in Siwa Oasis, economic development, and environmental quality (El-Said, 1999).

Data Analysis

The elements introduced in the analysis and assessment matrix are those with positive correlation in the problem-impact relationship under consideration. A list of these elements relevant to the assessment measures chosen in the study is given in Table (1).

In order to quantify changes in various components under consideration for assessment the system components were viewed as hardware, i.e., irrigation and drainage infrastructure; and software, i.e., socio-economy, health, behaviors, legislation, and environmental aspects. Then a comprehensive analysis is based on statistical analysis of results under the three considered measures was conducted to investigate the change in a given measure before and after management efforts, i.e., before and after the nineties. A series of interviews with local communities, government institution in Siwa, and various stakeholders was carried out for verification of analysis results.

External Feedback for Verification of Results

In addition to the field investigation work, and the subsequent analysis and assessment, a target group consists of representatives of various categories in the Oasis (with about 25 entities) of land and water users were interviewed. The aim of selecting all the categories is to insure real assessment of improvements. Based on the prevailing conditions, the following categories were identified

- The very few natives and locals who were very much involved in tourism, in small industries of local products and in small-scale agriculture (mainly date palm orchards).
- Poor landless farmers who have settled and are facing problems.
- Medium to large investors (transfer of technology).
- Local authorities, private reclamation individuals, agro-industries workers and new inhabitants.

Results of assessment were also reviewed and discussed with the stakeholder community in Siwa for feedback. Their feedback was an important factor for the final assessment and identifying suitable development schemes and recommendations for other closed basins in Egypt.

Table 1. Assessment of Implementation of Integrated Water Management Approach in Siwa

Category	Element	Main Problems	Impacts
Water Allocation	Economy	▪ Poor selection of developmental activities	▪ Poor or negative return from water
Water Management	Groundwater Management	▪ Poor design of wells ▪ Poor control of flowing wells ▪ Wasting of water	▪ Degradation of natural springs ▪ Loss of fresh water ▪ Increasing cost of water ▪ High water withdrawal technologies ▪ Drainage problems
	Water Distribution	▪ Inappropriate distribution systems (ag and domestic)	▪ High distribution losses ▪ Drainage problems
	Drainage	▪ High rates of drainage surplus ▪ Pollution from sewage	▪ Increasing cost of drainage infrastructure ▪ Less recycling opportunities ▪ Low water-use efficiencies ▪ Health problems
Agricultural development	Cropping pattern	▪ High consuming crops ▪ Poor utilization of comparable advantages	▪ Low economic return from water used in irrigation
	Irrigation practices	▪ Water wastage and low water-use efficiencies ▪ High irrigation cost	▪ Low added value from water
Environment	Ecology	▪ Loss of natural springs and habitat ▪ Soil salinity ▪ Introduction of polluted water bodies	▪ Ecological degradation ▪ Health problems
	Socio-economy	▪ Interference with cultural in heritage ▪ Loss of land ▪ Low income	▪ Less attraction ▪ Backward immigration ▪ Change of jobs
Institutions	Inter-institutional cooperation	▪ Increasing conflicts	▪ Adverse impacts on developments

RESULTS AND FINDINGS DISCUSSION

The results of the data analysis are presented in a comparative format showing pre- and post-implementation of the integrated management approach is presented in a concise graphical format. The historic value of each selected indicator measured or estimated in the first reconnaissance survey done by the MWRI in late sixties was considered as datum (baseline) of comparison. Those historic values of the selected indicators were considered baseline for comparison, as indicated in Figure 4.

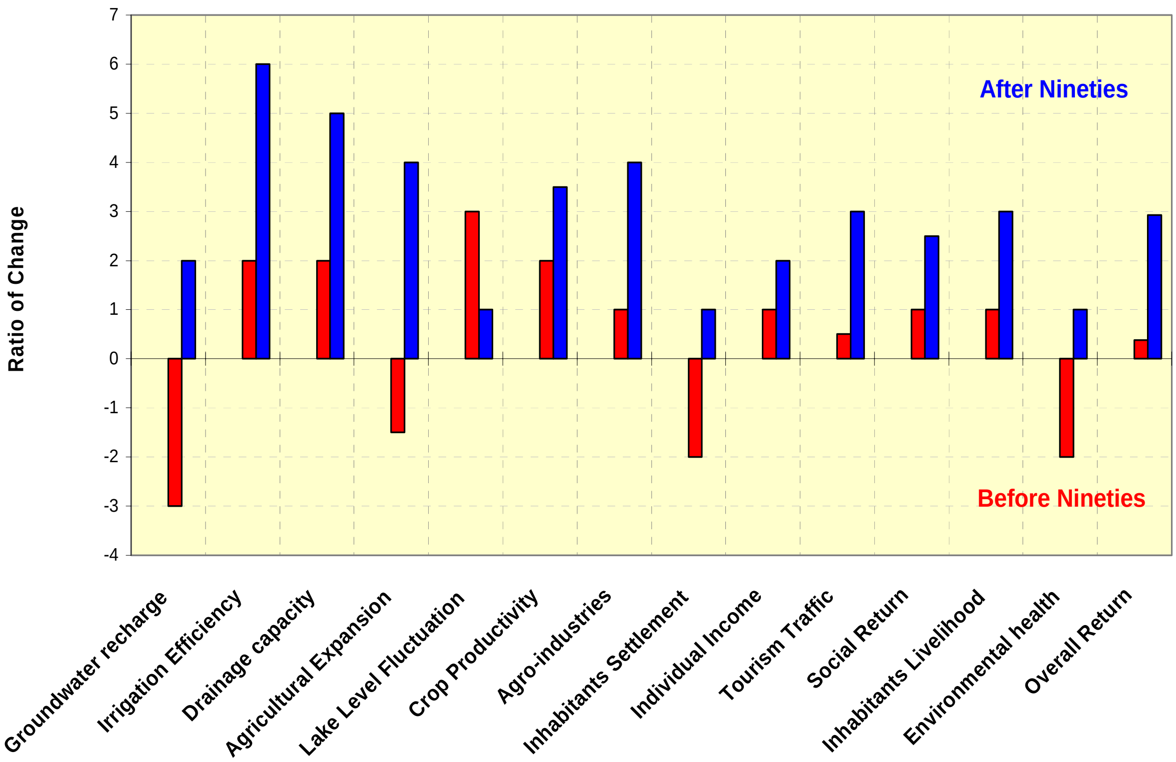


Figure 4. Outcome of the Assessment Study (Selected Indicators)
(Note: The historic values of the selected indicators were considered baseline for comparison)

Results indicated that the improvements in irrigation infrastructure undertaken by MWRI in cooperation with the stakeholders have increased irrigation efficiency in Siwa Oasis. It also confirmed an increased productivity of agriculture productivity in most of the Oasis lands. The promising finding was that the appropriate methods of irrigation could slow the pace of well-drilling and allow groundwater to recharge. It was also found that irrigation practices were strongly shaped by farmer involvement in choosing and operating irrigation systems. Consequently, a further study designed to let farmers in the newly formed WUA's to influence irrigation policies and water supplies more directly and to help extension agents distributing technical information promoting efficiency.

Disputes and conflicts over groundwater have been reduced, and the livelihood improvement of WUA farmers is 50% higher than those of non-members. Women representation inside WUA's is on a rise after implementing the awareness programs. Still, WUA's reinforce traditional power structures; richer farmers benefit most. Despite the mixed results, this much is clear: irrigation efficiency could only be improved with the collaboration of farmers and with practical insight into their daily experience on the land, patterns, erosion vulnerabilities, and potential new irrigation approaches to support the increasingly sedentary inhabitants and their herds.

The study outcome affirms the importance of socioeconomic considerations in shaping successful sustainable water-management. This outcome has serious implications on the development of societal awareness towards the value of participation in the decision-making-process that would lead to more open and democratic policies.

System evaluation and monitoring of practices for the study area of Siwa (MWRI, 2005) have provided useful lessons regarding the success of the implementation projects including,

- A proper management system to conserve and properly utilise precious water resources;
- Implementation of the District Water Board concept in the Oasis which allows pilot development in an institutionally relatively simple situation as compared to the Old (New) Lands of the Delta; and
- The experiences gained in the Oasis would feed the development of the concept in the much more complex situations in Old Lands both Old and New.

Further analysis of the study results has identified institutional and management practices deficiencies. This task was among the study objectives as a base to identify appropriate intervention actions to overcome the defined deficiencies. Table (2) summarizes analysis of results as it relates to problems, intervention identified, and mitigations.

Table 2. Summary of deficiencies and possible interventions

Issue / Problem	Possible Intervention	Mitigations
Institution entities	▪ Vision development through a regional water resources plan of New Lands, especially on institutional aspects ▪ IWRM with full participation of beneficiaries	▪ Commitment ▪ Policy framework ▪ Formation of water user organizations
Poor planning of land and water use with low economic return from water	▪ Select cash crops ▪ Appropriate irrigation systems ▪ Establish O&M procedures and practices	▪ Study market mechanisms ▪ Well-managed irrigation systems ▪ Stakeholder participation
Poor design of wells and distribution systems, leading to wasting water and low efficiency of water use	▪ Local IWRM plan ▪ Control of flowing wells ▪ Suitable location of wells ▪ Improved distribution systems ▪ Awareness	▪ Understanding of culture and practices ▪ Proper survey and understanding of conditions
Wasting water, low water use efficiency	▪ Separation of effluent ▪ Limit use of agro-chemicals ▪ Safe reuse of effluents	▪ Collection and disposal systems ▪ Awareness raising

CONCLUSIVE REMARKS

In recent years the GOE lead by MALR and MWRI has developed policies and tested practices crucial for development; agricultural reform; decentralization; user participation and private sector mobilization. While the policy environment is favorable for change, the application of new policies and practices outside the Old Lands are far from completion.

Structured Development that integrates societal values into water resources management plans of closed basins with the aim of improving the interaction of irrigation and drainage systems has not, yet met the expected outcome. Such efforts in Egypt were not introduced to the Western Desert Oases until the early nineties.

The environment of the New Lands of Egypt Western Desert Oases (closed basins) is very fragile. The only viable source of water is non-renewable groundwater. New settlers arrived to the oases for land reclamation and development. A significant cultural difference existed between the new settlers and the indigenous population, who developed sustainable small-scale agricultural systems over the last two millennia. The MWRI recognized that a higher level of integrated water resources management in other closed basin, e.g., Farafra, Baharia, Dakhla, and Kharga is required to assure sustainable development.

RECOMMENDATIONS AND THE ROAD AHEAD

Lessons learned during the course of this study have provided an insight into the fulfillment of integrating water resources development projects. The following recommendations are suggested for future integrated management in similar closed basins;

- Partnerships through strengthening water user organizations and empowering an appropriate institutional entity for the development of new lands and through institutionalizing private sector participation in decision-making and in financing of water management;

- Strengthening decentralized local institutional authorities, involving public and private entities, and encouraging and supporting participation of local governments in water management and water related services;

- Increased efficiency of water use and added value from water use through the development of an action plan for improved water management and related multi-objective plans including agriculture and agro-industry, implemented by the respective organizations; and

- Policy development and coordination through vision and methodology development, coordinated regional and local planning and strengthening institutionalized coordination and policy coherence mechanisms.

ACKNOWLEDGMENT

The author would like to thank specialists, researches, and field investigation teams from the Drainage Research Institute, Groundwater Research Institute, and Groundwater Sector at the Ministry of Water Resources and Irrigation for their valuable input and support. The author is also grateful to the experts of the Ministry and University of New Orleans in USA for their guidance, enlightening comments, and sincere review.

REFERENCES

Abdel-Gawadh, S. T., Kandil M., and Sadek T. M., 2002. Water Scarcity Prospects in Egypt 2000-2050, In: Markina, A., "Environmental Challenges in the Mediterranean 2002-2050", 2004 Kluwer Academic Publisher, Netherlands, p187-203.

Abu Hidb and Fu’ad., 1992, Reclamation of New lands and Their Utilization, Conference on Strategies of Egyptian Agriculture in the 1990s, Cairo. (in Arabic).

Abu-Zeid, Mahmoud, 2003. Water Vision for the Twenty- First Century in the Arab World, World Water Council, 3WWF, 2002

Advisory Panel Project on Water Management–APP, 2001. Workshop on Privatization / Sector reform Within MWRI: Roundtable discussion (Cairo-APP).

American Chamber, New Horizon for Development, Business Studies and Analysis Center, 2005

Bron, J., 2001, Involvement of Water users at field Level and Mandate, Water boards Project, In: Advisory Panel Project Workshop on Stakeholders Involvement in Water Management, Ismailia, Egypt, 8-9 January, 2001.

El-Said, Ibrahim Gamal, 1999, A Sociological Study of Value System in Some New Rural Communities In Egypt, Unpublished Ph.D. dissertation, Menoufya University.

Ministry of Investment of Egypt, 1997. Investment Law No. 8.

Ministry of Planning of Egypt, 2005. Achieving the Millennium Development Goals Successes and Challenges.

Ministry of Water Resources and Irrigation of Egypt, Expansion Sector, 2005. Evaluation of measures evolved by the Monitoring and Evaluation System fro Siwa Oasis. Technical Report, October 2005.

Ministry of Water Resources and Irrigation of Egypt, Groundwater Sector, 2001. The Groundwater Sector National Plan for Egypt, The Groundwater Sector Plan, National Level, September 2001.

Ministry of Water Resources and Irrigation of Egypt, Planning Sector, 2005. National Water Resources Plan for Egypt, Ground Water in the Western Desert, NWRP Technical Report No. 15, June 2001.

The World Bank, Rural Development, Water and Environment Department, Middle East and North Africa Region, 2002. Arab Republic of Egypt Cost Assessment of Environmental Degradation, Report No. 25175-EGT, June 29, 2002.

United Nation, 2002. Reporting on the Millennium Development Goals at the Country Level-Egypt, prepared by the Public Administration Research and Consultation Center (PARC), August 2002.

Water Boards Project, 2002. Proceeding of National Conference on Water Boards: a Board Base for Water Boards, Ain Sokhna, 30, January -2, February 2002. Website (http://www.uam.es/otroscentros/medina/Egypt/egypolcon.htm).

بيومي عطية، وفاطمة عبدالرحمن، 1998. إدارة الموارد المائية بجمهورية مصر العربية، ورقة مقدمة من وزارة الموارد المائية والري إلى المؤتمر الثالث عشر للعلميين المصريين بالخارج حول تنمية الصحراء في الألفية الثالثة، القاهرة، 28-30 ديسمبر 1998. (in Arabic)

محمد عبد المنعم شحاته ، وائل خيرى ، اشرف السيد ، يحيى حلبى ، 2004: الصرف الزراعى فى واحه سيوه من منظور اجتماعى متكامل ، نشرت بمجلة علوم المياه التى يصدها المركز القومى لبحوث المياه (عدد 36 فى أكتوبر(2004 (in Arabic)

NEW STRATEGIES OF DONORS IN THE IRRIGATION SECTOR IN AFRICA

Hervé Lévite[1]
Mayouma Loumouamou[2]
Florent Maraux[3]
Julienne Roux[4]
Estelle Godart[5]

ABSTRACT

In 2005, FAO released an "Irrigation in Africa in figures" report which emphasized that the level of investment in agricultural water management has been declining for the past two decades. In response to the UN Millennium Development Goals and recurring food crises in Africa, political initiatives are being pursued such as the UK-led Commission for Africa. The report called for a huge effort in the irrigation sector with a plea to double the area of arable land under irrigation by 2015. Today the World Bank appears to lead the process of re-engagement in the sector. But only few donors seem ready to follow the momentum. In fact there are still a lot of doubts on: how to invest in a continent where irrigation is so risky with high costs, unreliable operation and maintenance, weak institutions, and meagre markets. Besides, new considerations call for prudence in irrigation development such as competition for water (growing urbanization, wetlands protections), climate change, and agriculture trade globalisation.

The aim of this paper is to try to describe the current donors' approaches and the coherence of their strategies. Indeed the Paris Declaration on Aid Effectiveness obliges donors to adapt to countries' demand and to harmonize their policies. It appears that in the irrigation sector donors do not have yet explicit strategies in Sub Saharan Africa. Several donors are not even certain that irrigation is a good entry point to solve poverty and food security problems, despite recent evidence brought about by the research community.

INTRODUCTION

There now seems to be a general consensus on the need to re-invest in water for agriculture in Sub-Saharan Africa (SSA). Unquestionably the topic is on the agenda of African leaders. It has been discussed during international meetings such as the World Water Forum IV in 2006. In the last couple of years different organisations such as the New Partnership for African Development (NEPAD) with the assistance of FAO, the Commission for Africa as well as G8 initiatives made the case for African irrigation development. But for the moment only few donors are trying to keep the momentum. Indeed on the field things are moving very slowly and many donors seem to have chosen "a wait and see" approach. Public investment is three to fourth times less than

[1] Technical Officer, IPTRID-FAO, Rome (Italy); herve.levite@fao.org
[2] Master student ENGREF, Montpellier (France); lmayouma@yahoo.fr
[3] Senior Researcher CIRAD, Montpellier (France); florent.maraux@cirad.fr
[4] Junior Professional Officer, World Bank, Washington (USA); jroux@worldbank.org
[5] Officer in charge of the irrigation sector, French Ministry of Foreign Affairs, Paris (France); Estelle.GODART@diplomatie.gouv.fr

expected by NEPAD. Why are investment levels so low? That is the central question we would like to explore in this paper.

This work has been carried out by a master student who has investigated to which extent donors are preparing action plans and reengaging in a context of aid harmonisation. It should be considered more as a reflection in course than an exhaustive work and does not reflect necessarily the views of FAO.

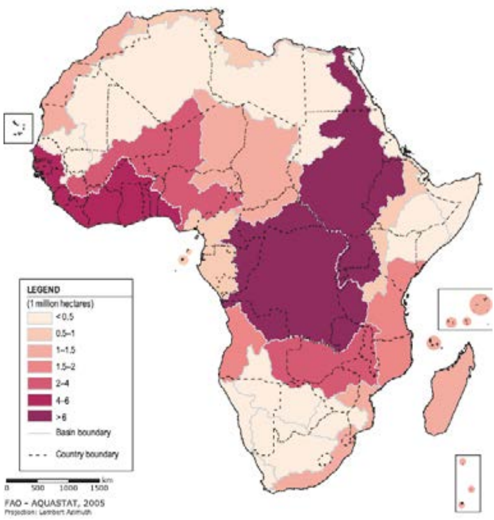
A NEED FOR INVESTING IN AGRICULTURAL WATER MANAGEMENT IN SUB-SAHARAN AFRICA

An unquestionable need

Hunger and malnutrition are affecting the African continent in a dreadful manner. A large percentage of the population (33%), especially the youngest, is undernourished: when the world average calorie daily intake is reaching 2800 kcal per person, SSA remains at the level of 2500 kcal/p/d, with a large proportion (more than 250 million people) under 2000 kcal. Even when enough food is produced locally, poverty does not allow individuals to buy this food, as it was probably the case during the 2005 famine in Niger. In SSA the proportion of poor people is indeed the highest worldwide. When food crises occur due to conflicts or natural disasters (such as droughts, floods and epidemics), very costly mechanisms (through World Food Programme or NGOs) take over, with probably unconstructive consequences on local agriculture. It is even estimated (APF 2006) that between 1993 and 2003 food production has declined in SSA. Fertilizers are little used (9 kg/ha compared to 220 kg/ha in East Asia) and soil mining is a serious issue, as is general land degradation. The share of world trade for 9 of 10 of SSA major agricultural exports has decreased (APF 2006). Finally, all projections confirm that the population in SSA will continue to grow at an impressive rate (around 3 % per year). Although the recent years have witnessed a good economic growth, the situation might not appear to have changed much over the past 20 years, and even some factors make it worse, with new burdens threatening the continent such as HIV/AIDS, conflicts, rapid urbanization, increasing cost of energy and ultimately climate change. Lastly human migration - inside the continent as well as outside, especially Europe – is still at preoccupying levels with migrants cynically called “environmental refugees” (Myers, 2005)

An untapped potential

However it would be possible to produce enough food for the African population, thanks to both rainfed and irrigated agriculture. There is for instance a huge untapped potential for irrigation development. According to FAO (FAO, 2005), only around 9 million hectares of land in SSA are under some form of water management and 7 million are equipped, figure to be compared with 234 million hectares of the whole developing world. Of these 7 million probably 2 million are not exploited (World Water Forum IV). Water withdrawals for agriculture are very limited – just under 3% of the total renewable water resource – and water storage is well below the levels in other regions. As figure 1 shows the potential is thus immense in a continent where a large number of food commodities are in fact imported, and at a high cost. And even when water is available, the majority of countries of SSA have not access since they are suffering from an “economic water scarcity” **(**See figure 2, Seckler *et al* 1998)**.** Indeed countries are almost entirely dependent on external aid for such costly investments. Private investments are yet scarce, partly because investments are risky in Africa in a context of low commodities prices. On the other hand there is a huge spontaneous development of the informal (and private) irrigation, especially in peri-urban areas, that is not appearing in official statistics (Drechsel, 2006).



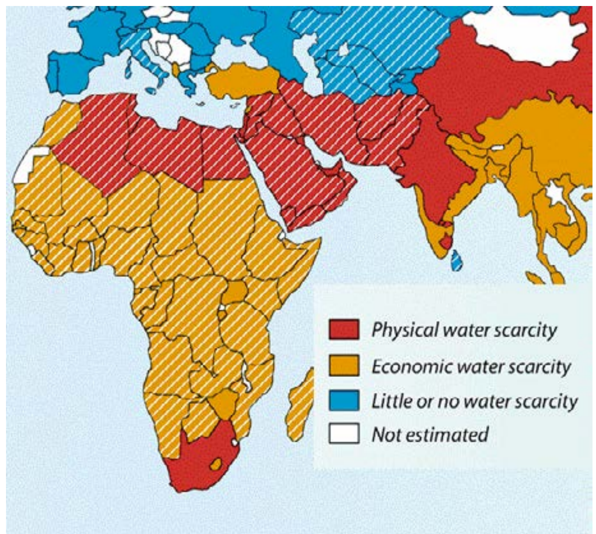


Figure 1. FAO, 2005 Irrigation potential by river basin (the reddish show large potential) and Figure 2 IWMI water scarcity map (Seckler 1998)

The magnitude of the effort needed

Future food demand can not be covered only by intensification of rainfed agriculture, it will require increased agricultural water management as well (FAO, 2003). Irrigation development should then play a valuable role to achieve the objective of eradicating extreme poverty and hunger, objective 1 of the Millennium Development Goals of the United Nations (2000). In this perspective many initiatives such as the Comprehensive Africa Agriculture Development Programme (CAADP) in cooperation with FAO (NEPAD 2002), or the Commission for Africa (Westby et al, 2005), have tried to evaluate the magnitude of the effort required. Of course views are differing (table 1) but there is a consensus that substantial funding is needed in the sector.

Table 1. Rough estimates of the investments needs targets

	New areas to be irrigated by 2015	Mean annual rate	Magnitude of total cost
FAO "business as usual scenario" (between 2002-2015) FAO, 2005	2 M ha	1.1 %	
CAADP 2002 (NEPAD 2002)	10 M ha	more than 5 %	37 billion US $ for the whole Africa in 14 years
Commission for Africa, 2005 (Lankford in Westby et al)	5 M ha	3.8 %	20 billion US$ in 10 years

ANALYSIS OF PAST EXPERIENCES

The "negative image of irrigation"

It appears that the donors' community is adopting a cautious approach in re-engaging in agriculture water management. There are three main reasons for that:

- First, commodity prices are still low. As it has been shown before (Thompson, 2001) lending and prices seem to be well correlated. Only recent rise of cereals prices in 2006 (60 % on maize for instance in 2006) has reversed the long-established trend. Increased global population, changing diets, and expansion in biofuel use might continue push prices in the future but there is no certainty as to the direction of future price changes.

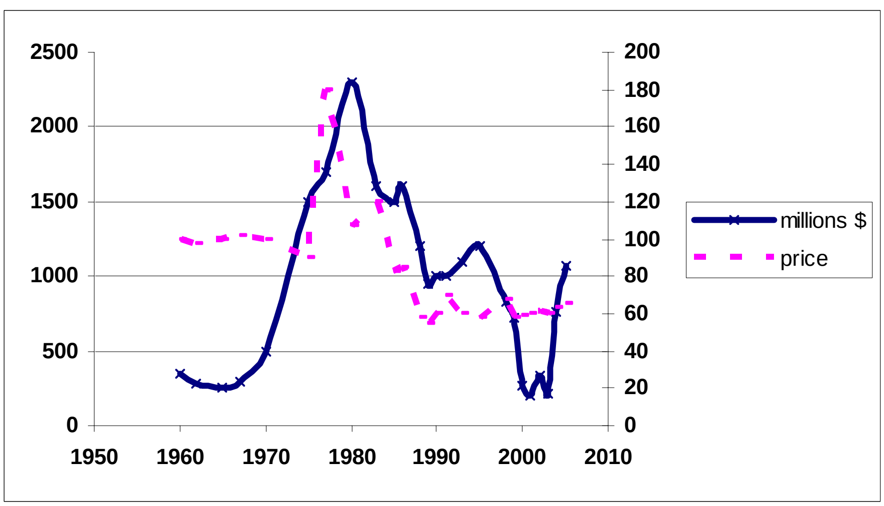


Figure 3. Food prices (right scale - index 100 in 1960) and WB lending (left scale adapted from Thomson ICID in ICID Seoul 2001, Joachim von Braun IFPRI, 2005 and J. Roux 2007)

Moreover, difficulties to transform, transport and market properly the products in Africa are also of major concern. Finally, the deficiency of good market regulations and the often-poor competitiveness with cheap imported food (for instance rice from Asia in Senegal) are also serious issues.

- Secondly, it is commonly assumed that irrigation projects in SAA have often failed in the past, mainly because of poor management and poor integration in a competitive agricultural production system. The most traditional investment models have been schemes run by state agencies, with little control by farmers. Donors have turned away from such schemes that are financially unsustainable and poorly operated. More recently, other types of investments have been promoted, such as community led medium-sized schemes, but difficulties still abound, such as high cost of infrastructure development, or lack of accompanying infrastructure such as market access.

- Thirdly, many large projects have had some negative externalities: impacts on human health, on the environment (salinization, erosion after deforestation, pollution), and on population displacements. The work of the World Commission on Dams released in 2000 has been probably a major driver in the late 1990s for disengagement of donors in large-scale water infrastructure construction.

The lessons of a new collaborative study

In order to move forward on this difficult subject, and to follow the path initiated by NEPAD in CAADP, three major donors, World Bank (WB) International Fund for Agricultural Development (IFAD) and African Development Bank (AfDB) have launched a collaborative Program on Agricultural Water Investment Strategies in Sub-Saharan Africa, with the support of FAO and the International Water Management Institute (IWMI). The idea was to draw lessons from past experiences and to pave the way for a more strategic reengagement in agricultural water investments. A number of studies have been carried out as. From this work, the two main results are:

a) Some conclusions of the studies confirm the previous impressions

- Overall, irrigated production in SSA is generally characterized by low productivity
- Project design has been largely top down.
- Many investments have been made that were driven by strategic or political reasons rather than by economic profitability New participatory approaches give better results.
- Farmer empowerment and participation are key to improving project quality.
- Institutional capacity building is very important.

b) But conventional wisdom is being challenged

- Costs of successful Irrigation Projects in SSA can be comparable with those in Asia, when leaving out “monumental failures”, and new generation, better designed irrigation projects are not much more costly than those in other regions.
- Although there were many failures in the 1970s and 1980s, recent projects have generally had acceptable rates of return.
- There have been successful recent project investments in small-scale community managed irrigation.

- Individual market driven investments by smallholders with low cost technology, and support to supply chains and marketing have also done well.
- There are examples of successful public investment in large-scale irrigation
- There is scope for private sector involvement
- There are increasing market opportunities, with prices of commodities on the rise again, and new niches, such as biofuels under fast development.

These conclusions of this “donor driven” study could have already some impact on donors’ opinion about irrigation in SSA, but what is their current position ?

WHAT ARE THE TRENDS IN INVESTMENTS IN SSA?

Water aid is on the rise again in a general context of growth of aid

According to OECD, worldwide aid in the water sector (around 7 % of the total investment of aid) has declined in the nineties and has picked up again in the early 2000s (fig 4). But it is quite difficult to isolate in OECD statistics, the real participation of donors in irrigation and drainage projects. What we know is that Water supply and Sanitation projects are dominating the picture, and Integrated Water Resources Management has attracted a lot of attention as well.

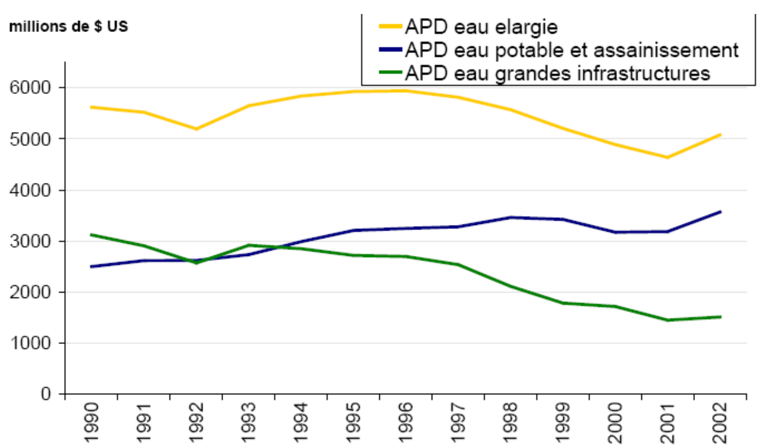


Figure 4. International aid in the water sector
(World Water Council- Aide Publique au développement 1990-2004 WWF4 : in yellow all sectors related to water, in green large infrastructure, in blue : potable water and sanitation)

One could mention for example the Nile Basin Initiative or the Niger basin Authority. This prudence on the irrigation sector is confirmed when we look at bilateral aid as well. Among the 11 main bilateral donors involved in SSA (Germany, France, Denmark, UK, Netherlands, Italy, Sweden, USAID, Canada, Finland and Norway), no one is really pushing on irrigation development in its national aid strategy. Some donors such as UK or France are proposing to double the amount of aid in this water sector but wish both to concentrate their efforts on water supply and sanitation. The endeavour towards irrigation in SSA is more multilateral at the moment for the last 5 years, and approximated 20 M$ from the EU, probably 50 M$ from IFAD, 200 M$ from the African development Bank, and 280 M$ from the World Bank. After some years of neglect for the I&D sector world-wide, the World Bank (WB) has decided to boost the topic though its “Re-engaging in Agricultural Water Management report” in 2006 and the launching of new dedicated projects. Investments in irrigation in SSA by the World Bank have quadrupled from 2004 to 2007.

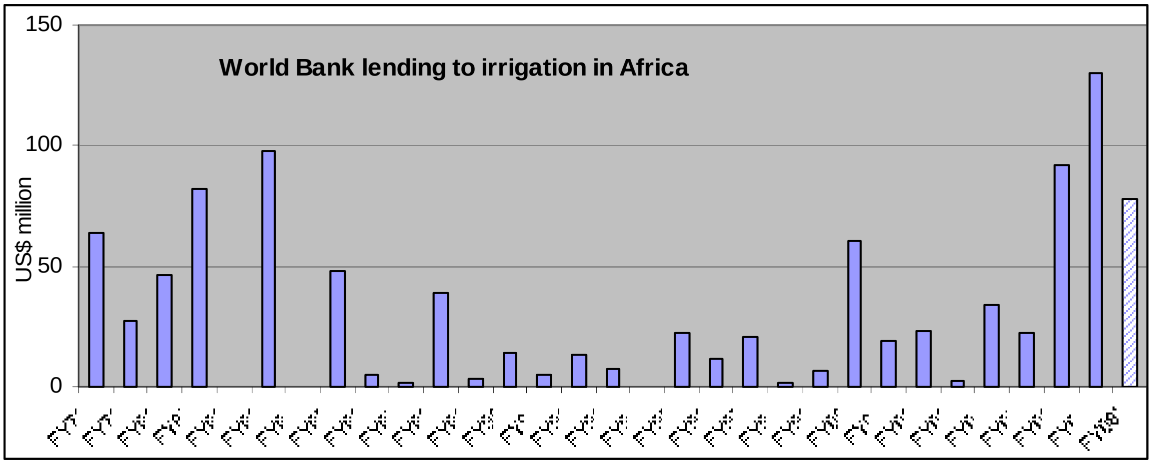


Figure 5. 20 years of World bank lending to irrigation in Africa. From J. Roux, 2007
Note: FY = Fiscal Year. FY08 is an estimate

But multi-donor re-engagement in irrigation has not been manifest yet in SSA

The World Bank recognizes that commitments on Irrigation and Drainage in Africa are still low and represent only 5 percent of the total Bank I&D portfolio, when commitments in other regions (Asia in particular) average several hundreds million $ each year. Furthermore the recent review of the progress of the CAADP done in Moscow in 2006 by the African Partnership Forum gives a bleak image of the situation : in terms of evaluation of results, the pillar number 1 (land and water management) is considered as having been partially achieved only (APF, 2006).

DONORS' ORIENTATIONS

Donors should now follow the principles of aid harmonisation, as stated in particular in the 2005 Paris Declaration on Aid effectiveness. No donor should any longer “play alone”. The Declaration also brings ownership of investment decisions back to the countries or Regional Economic Commissions. Donors must accept then the views of national partners, which might take some time if there is not yet solid national water or irrigation policies.

From a literature review and after exchanging with a number of key donors, we found three types of results:

a) In the irrigation sector, there is not yet any formal platform where agreement on donors' strategies are discussed. Some hubs exist such as the donor platform for rural development http://www.donorplatform.org/, but without influence yet in the sector.

b) Some key principles seem to be well accepted by all donors

- **Irrigation projects should be developed in a basin framework**

The Integrated Water Resource Management principle (even IWRLandM) is the key word, at national or transboundary level. The aim is to avoid negative impacts of investments and optimise water allocation. Amongst the principles of IWRM, environmental sustainability is the main concern (wetlands protection and minimum flows in rivers).

- **Farmers participation is deemed essential**

Irrigation is a collective activity. This is true even for individual farmers who need to share the resource (for example the groundwater source). Irrigation investments are successful at the end of the day only if they are valuable tools available for farmers. Efforts to accompany farmers (organisations, water users associations, capacity building) must not be neglected. A renewed interest on local know-how would also be necessary. In other terms, investments should prioritize farmer-led projects, and respond to farmers' needs.

- **Policies and institutions must be comprehensible**

An enabling environment is key for success. Projects have to be embedded in clear national policies and at the moment, irrigation is too often stretched in the hands of two (or more) different ministries such as Agriculture and Water (Burke 2002). Clarification on agricultural strategies, water management strategies, land tenure and integration is thus mandatory. In the countries themselves, Poverty Reduction Strategic Papers, which should be one of the main instrument for donor coordination, mention little, if not at all, I&D aspects.

- **No specific irrigation technique is promoted**

At this stage, water saving is not the main priority in SSA (which is not the case for example in Northern Africa). But now efforts will bear on the whole water cycle and cover all water uses, which is something relatively new. Enhancing rainfed agriculture, developing rainwater harvesting or groundwater, or constructing irrigation infrastructure should be considered in a comprehensive perspective. Integration of agricultural water management in the context of micro catchments management is already a focus area for some interventions (such as WB or AFD in Madagascar projects). Conservation Agriculture is promoted by the French AFD as a priority (Gilard, 2006). Additional research is needed to this end. Finally as said before, traditional techniques (soil and water conservation and water harvesting techniques) are also important entry points.

- **Gender aspects**

Are now widely shared. However it is difficult to ensure that irrigation provides direct and lasting benefits to women. In 2000, IFAD conducted a thematic study of irrigation water user associations (WUAs) under IFAD-supported projects in all regions.(IFAD 2001) The review found that only one third of the projects stressed gender issues and strategies. Usually, the *gender goals* of the projects included:

- preferential treatment of women farmers in the allocation of newly irrigated land;
- promotion of women's participation in the water user associations; and
- training and organization of women farmers.

However, as far as gender aspects are considered, it would be easy to demonstrate that small scale irrigation provides better opportunities for women to undertake initiatives, through effective women's associations.

c) Some differences remain in the approaches

- **Market orientation vs livelihoods approach**

The real debate is around market oriented production or livelihood approach (rural employment - more job per crop- and poverty reduction). IFAD for instance promotes direct pro-poor projects when the World Bank wishes economic growth to be the engine of poverty reduction, and sees financial profitability as the surest way to ensure sustainability of schemes. Should irrigated agriculture being then only commercially oriented? To which extent? Also, the vision of World Bank is to see increased private sector involvement in irrigation, that would bring in finance and expertise (development of commercial estates with outgrower schemes or public private partnerships for example).

- **Changing crops**

Consequently, there is still a strong debate about the choice of crops : cash crops for export or staple food. Do we need to promote national food self-sufficiency or to let the market decide the orientations? Finally the cost for the SSA countries (in terms of food imports) is huge, as it is for the international community on food aid through WFP. The debate is still very complicated with civil society movements (such as the food sovereignty promoted by Via Campesina Movement) or even the "right to food" promoted by the UN system.

- **Size of irrigation projects**

We know that large water infrastructures (dams in particular) will be part of the picture in. But dams will be built as multiple use facilities with electricity, drinkable water, irrigation and flow regulation as key functions. For two reasons: the huge cost of fossil energy and the return rate of projects that is really superior when multiples uses are taken into consideration.
However, there is no consensus yet on the size of the irrigation schemes that have to be promoted (small scale, village based, large scale). Small scale irrigation seems to receive a large share of attention from the Commission for Africa (Lankford 2005). But it was debated during the last World Water Forum that "one should not be to dogmatic about size of projects; the debate about small versus medium versus large is not meaningful, and each type has a suitable place".

- **Cost recovery**

Questions on water pricing and cost recovery are central. The aim of water fees are first to cover operation and maintenance costs and also to encourage farmers to save water (Easter 2005). But in SSA this is still exception and it poses a threat. The task force on financing water for all (WWC 2006) said that the fact that irrigation water provided from public schemes is either free or massively under-priced it is a fundamental obstacle to investment. Finally what kind of cost recovery do we need to put in place; must it be full or partial? Donors all support the principle of cost recovery to but do not seem to have taken any strong position on the desirable level (whether to recover investment costs, or part of operation and maintenance costs).

COUNTRY MOBILISATION

Now investment projects should be truly owned and promoted by countries. But Poverty Reduction Strategic Papers yet contain little on irrigation, as explain above. Therefore, it is expected that countries will put in place specific strategies, policies, and master plans to guide interventions in the sector. Related policies should in any case be clarified, especially those with regard to land tenure problems. Already some countries have engaged in the development of comprehensive irrigation strategies (Zambia for example), and are translating the recommendations in action by proposing bankable projects under CAADP with FAO assistance. In some cases, involvement of Regional Economic Commissions might be required (for integration in regional problems, or trans-border projects). In West Africa, ECOWAS has been particularly dynamic in the last couple of years with the creation of a Water Unit in charge of providing information on best practices of water management as well as funding mechanisms an opportunities.(http://www.wrcu.ecowas.int/en/pdf/Financinguidefinal.pdf)

Role of ICID

Lastly, and importantly enough, it seems that the role of the national committees in irrigation and drainage could be valorised. There are 27 national committees on the whole continent (out of 53 countries), including 21 in SSA, These committees could advocate locally on the need for investment, and they could also support strategic efforts in the country. In Mali for example, the Malian ICID committee (AMID) has recently welcomed a national workshop (July 2006) on small scale irrigation development. The South Africa National Committee on Irrigation and drainage (SANCID) on the other hand is very committed to new reflections for the region. Sub regional committees such as the Regional Association on Irrigation and Drainage in West and Central Africa (RAID-ARID) also have an important role to play, and they are now extremely active. ARID organised in 2005 a major, and successful, professional show (http://www.arid-afrique.org/rubrique.php?id_rubrique=2). In March 2007, it has been a relay of the World Bank, FAO, IFAD, AfDB, and IWMI efforts on “Scaling up Agricultural water management in SSA”, with a strong Ouagadougou Call for Action, mobilising professionals from the whole continent as well as donors (the above plus DFID, France, Japan) towards reinvestment in the sector.

CONCLUDING REMARKS

Despite the intention of the Paris Declaration on aid harmonization, we found that there is no obvious harmonisation yet of donors on irrigation interventions in SSA. Perhaps there is still no clear consensus on how to reduce rural poverty and invest in irrigation. However, common understanding has been developed on a number of issues and aspects, which is a real progress. But the level of investment in irrigation is not yet satisfactory. There is a risk to waste time since the capacity of "absorption of funds" is limited in the continent. And we advocate that there is a danger that, after crises, projects would be done again precipitously. If the project cycle is shortened and planning and implementation is not properly done, the risk of failure is higher (Morardet et al 2005). Finally, it seems that new comers in Africa (China, Brazil, India) are interested in investing in the sector. We hope they could also take care of lessons of the past. Finally private companies seems also interested by new lands made available by several governments (such as Mali, Nigeria, Mozambique) but for biofuels, cotton, tobacco or other non-edible commodities production, posing a new challenge to the already difficult equation on food security in the continent.

REFERENCES

ADB, FAO, IFAD, IWMI, World Bank. Investment in Agricultural Water for Poverty Reduction and Economic Growth in Sub-Saharan Africa. Synthesis Report. Draft February 21, 2007. http://siteresources.worldbank.org/RPDLPROGRAM/Resources/459596-1170984095733/synthesisreport.pdf

APF Africa Partnership Forum. Progress report: Agriculture. Moscow 2006 (http://www.donorplatform.org/index.php?option=com_docman&task=doc_view&gid=382&Itemid=37&PHPSESSID=644acd6bb8662a855ebcecc6ddb1c87c)

Burke, J.J. 2002. Implementation of national irrigation strategies: fuzzy vision, harsh realities and strange bedfellows. (http://Inweb18.worldbank.org/ESSD/essdext.nsf/18DocByUnid/8E30387F8BC5877985256BE900763C6C?Opendocument

FAO 2003 Unlocking the Water Potential of Agriculture. Rome

FAO 2005 Irrigation in Africa in figures. FAO Water Report 29. Rome

FAO 2006 Demand for products of irrigated agriculture in SSA FAO Water Report 31.

IWMI. Collaborative Program on Agricultural Water Investment Strategies in Sub-Saharan Africa: Trends and Opportunities http://www.iwmi.cgiar.org/africanwaterinvestment

Drechsel, P.; Graefe, S.; Sonou, M.; Cofie, O. 2006. Informal irrigation in urban West Africa: An overview. Colombo, Sri Lanka: International Water Management Institute. 40.p. (IWMI Research Report 102)

Easter William and Yang Liu 2005 Cost recovery and water pricing for irrigation and drainage projects
http://siteresources.worldbank.org/INTARD/Resources/Cost_Recovery_and_Water_Pricing_final_note.pdf

Gilard O. 2006.– Eau et agriculture. Quel cadre conceptuel pour les interventions de l'AFD ? Note de réflexion interne AFD

IFAD knowledge notes. IFAD's Rural Poverty Report 2001; (http://www.ifad.org/poverty/)

IFPRI von Braun 2005 The World Food situation
http://www.ifpri.org/pubs/agm05/jvbagm2005.asp#read

Lankford, BA (2005) Rural infrastructure to contribute to African agricultural development: the case of irrigation. Report for The Commission for Africa, ODG, University of East Anglia, Norwich
(http://www.commissionforafrica.org/english/report/background/westby_et_al_background.pdf)

Loumouamou Mayouma. 2007 Les axes d'intervention des bailleurs de fonds en Afrique Subsaharienne pour la gestion de l'eau agricole. Draft Synthèse bibliographique ENGREF Montpellier France

Morardet, S.; Merrey, D.J.; Seshoka, J.; Sally, H. 2005. Improving irrigation project planning and implementation processes in Sub-Saharan Africa: Diagnosis and recommendations. Colombo, Sri Lanka: IWMI. 91p. (Working paper 99)

Myers, Norman 2005 OSCE 13 th Economic forum Prague 29-27 May 2005
www.osce.org/documents/eea/2005/05/14488_en.pdf

NEPAD 2002 Comprehensive Africa Agriculture Development Programme (CAADP),
http://www.fao.org/docrep/005/y6831e/y6831e00.htm

Roux Julienne 2006 World Bank lending in Africa. Internal Notes Washington

Seckler, D., Amarasinghe U., Molden D. de Silva R., and Barker R. 1998. World water demand and supply, 1990 to 2025: Scenarios and issues. Research Report 19. Colombo, Sri Lanka: International Water Management Institute.

Thompson, R.L. 2001. The World Bank strategy to rural development with special reference to the role of irrigation and drainage. Keynote address. 1st Asian Regional Conference and Workshop on the Occasion of 52nd IEC meeting of ICID, Seoul. New Delhi, ICID. pp. 2 – 17

World Bank 2006, Reengaging in agricultural water management
http://siteresources.worldbank.org/INTARD/Resources/DID_AWM.pdf

World Bank. Regional workshop on Scaling Up Agricultural Water Development in Sub-Saharan Africa. Ouagadougou, Burkina Faso. March 26-28, 2007 http://go.worldbank.org/T9SLNYEO10

World Commission on Dams, 2000 “Dams and Development: A New Framework for Decision-making (http://www.dams.org/report/)

World Water Council 2006 Task Force on Financing Water for All

World Water forum 4 - session FT4 24 Investment in Agricultural Water Management in Sub-Saharan Africa: Diagnosis of Trends and Opportunities http://www.worldwaterforum.org/files/SessionSummaries/FT4_24_SESSION%20REPORT.pdf)

HOLISTIC PERSPECTIVE FOR INVESTMENTS IN AGRICULTURAL DRAINAGE IN EGYPT

M.A.S. Wahba[1]
M.H. Amer[2]

ABSTRACT

During the last 30-40 years, Egypt has implemented one of the largest drainage networks in the world, consisting of surface drains, subsurface drains, pump stations and other related works. The target area to be provided with subsurface drainage in Egypt is 6.4 million acres out of which about 5.5 million acres is already implemented. Subsurface drainage systems in Egypt have reached the stage that more areas installed have, in theory, passed their economic lifetime and these areas need rehabilitation.

The overall cost of installation of subsurface drainage in Egypt is estimated at EGP 1600 per acre (year 2007), and about EGP 900 per acre for rehabilitation of old drainage systems. Maintenance costs are estimated at EGP 50 per acre per year. The pay back period of drainage is not more than 3-4 years. Incremental benefits of improved drainage on productivity amount to US $ 250 – 350, per hectare depending on location and soils.

Recently, a new role for drainage as a complementary part of the integrated water resources management has been recognized and the benefits of drainage went beyond reducing soil salinity and increasing crop yields. For that reason a new view for the drainage investment is needed which take into consideration all the benefits and impacts and the expected changes in all levels of planning, implementing, operating, maintaining and managing the new and old drainage systems.

The objective of this paper is to identify the current and future investments of agriculture drainage for a sustainable agricultural production in Egypt. In spite of the great achievements and benefits of drainage in Egypt, there is a huge potential for investments are needed to sustain agricultural drainage against the future challenges.

INTRODUCTION

Irrigated agriculture represents only 17 percent of total land cropped in the world, but provides 40 percent of the world's food. It is expected that irrigated agriculture will provide close to two-thirds of the additional food needed over the next 25 years. There is still some potential to expand irrigated area, which could be increased by up to 20 percent (40 million hectares) over the next 25 years.

[1] Dr. Mohamed Abdel-Moneim Shehata Wahba: Senior Researcher, Drainage Research Institute (DRI), NWRC, Egypt. Tel: 002024464505- 002024464626, Fax:002024464504 .mswahba@hotmail.com, .encid@link.com.eg
[2] Dr. Mohamed Hassan Amer: Professor Emeritus, National Water Research Center (NWRC), Cairo, Egypt and Chairman of ENCID. email: .encid@link.com.eg

Poor irrigation and agronomic practices have led salinity, sodicity, and waterlogging to affect 40-50 percent of the world's 270 million hectares of land currently under irrigation. Proper management and provision for subsurface drainage in irrigation systems can address waterlogging and salinity problems and enhance productivity and sustainability of irrigation system. Drainage investments are needed to control waterlogging and salinity on 60-85 million hectares of currently irrigated lands. This investment can yield significant economic benefits (World Bank, 2006)

Drainage plays an essential part in food production while safeguarding the investments in irrigation and conserving land resources. During the second half of the 20th Century, drainage was implemented in about 150 million hectares of under-producing and naturally waterlogged or salinized lands, in many parts of the world.

Drainage has also contributed to agricultural intensification and diversification and as such has made the agricultural sector more competitive and financially sustainable. In global terms, however, drainage is still far of being adequate or sufficient. Out of the worldwide 1500 million ha of irrigated and rainfed cropped land, only about 14% is provided with some form of artificial drainage. In arid and semi-arid areas some 20 to 30 million ha suffer from irrigation induced degradation resulting in water logging and high soil salinity (ICID Statistics, 2003).

About US$20.7 billion has been spent by the World Bank for irrigation and drainage investments since 1980, but a reduced level of funding has been reported in recent years, dropping from US$1,040 million per year during 1994-96 to US$891 million per year in 1997-99, and US$490 million per year in 2000-02 (World Bank, 2006).

Since the 1970s about US$3 billion in Egypt has been invested to provide drainage for 2 million hectares for mitigation the effect of the irrigation-induced on water-logging and salinity. These investments lead to adopting appropriate technologies, improving irrigation systems, transferring management to water users associations, and adopting a well-functioning system of cost recovery. Egypt has a cropping intensity of 200 percent, and crop yields for wheat, rice, and cotton are among the highest in the world. Improved drainage accounts for 15-25 percent of crop yield increases (World Bank 2002).

Nowadays a new role for drainage has been recognized as an complementary part of the integrated water resources system. An integrated approach (DRAINFRAME), addressing all positive and negative impacts of drainage has been introduced by Abdel-Dayem et al 2004, which shows how a participatory planning methodology looking at every aspect of the resource system and all the stakeholders can untangle the multiple impacts, costs, and benefits; prioritize investments; and begin to locate benefits and mitigate side effects.

The objective of this paper is to identify the current and future investments of agriculture drainage for sustainable agricultural production in Egypt.

Drainage in Egypt

Egypt's Nile Valley and Delta, one of the oldest agricultural areas in the world, has been under continuous cultivation for at least 5000 years. Egypt has an arid climate, characterized by high evaporation rates (1500-2400 mm/year) and little rainfall (5-200 mm/year), thus agriculture mainly depends on irrigation from the river Nile (Fig 1). In the 1960's, the Egyptian Government started an ambitious programme to implement drainage system in approximately 2.5 million ha of agricultural land with an annual implementation capacity of about 70 000 ha and it is expected to be completed around 2012 (Nijland et al 2005).

The implementation of drainage systems involves the following steps:

- Construction of open main drains or the remodeling of the existing main surface drains
- Construction of drainage pumping stations to keep the water level in the main surface drains at 2.5 m below field level so that the pipe systems can discharge by gravity in these main drains;
- Construction of pipe field drainage systems consisting of field drains and pipe collector drains.

The overall cost of installation of subsurface drainage in Egypt is estimated at EGP 1600 per acre (year 2007), and about EGP/900/ acres for rehabilitation of old drainage systems. Maintenance costs are estimated at EGP 50 per acre per year. Assuming that 2/3 of incremental income can be attributed to drainage; this would mean that the payback period of drainage is not more than 3-4 years. Drainage is one of the most important investments for raising agricultural productivity in a country with limited water resources and high population growth. Drainage is estimated to have an economic rate of return of 19 percent. The annual contribution of drainage to the Gross Domestic Product was estimated at US$0.9 billion or 8 percent of agricultural value added (Ali et al 2001).

Cost recovery for drainage investments and maintenance has improved, as is reflected in a 25-year time frame for full recovery of capital costs, shared between government (50-55 percent) and beneficiaries (40-45 percent) (World Bank, 2006).

DRIVERS FOR INVESTMENT IN EGYPT

The pressure of fast growing population

The growing population of Egypt and related industrial and agricultural activities has increased the demand for water and land to a level that reaches the limits of the available supply. The population of Egypt has been growing in the last 50 years from 19 million in year 1947 to about 38 million in the year 1977 to 66 million in 2002 and 70 million in the year 2005, with an annual increase of about 1.4 million. It is expected to grow to 83 million in the year 2017 and to be about 95 million by the year 2025 (see fig. 2).

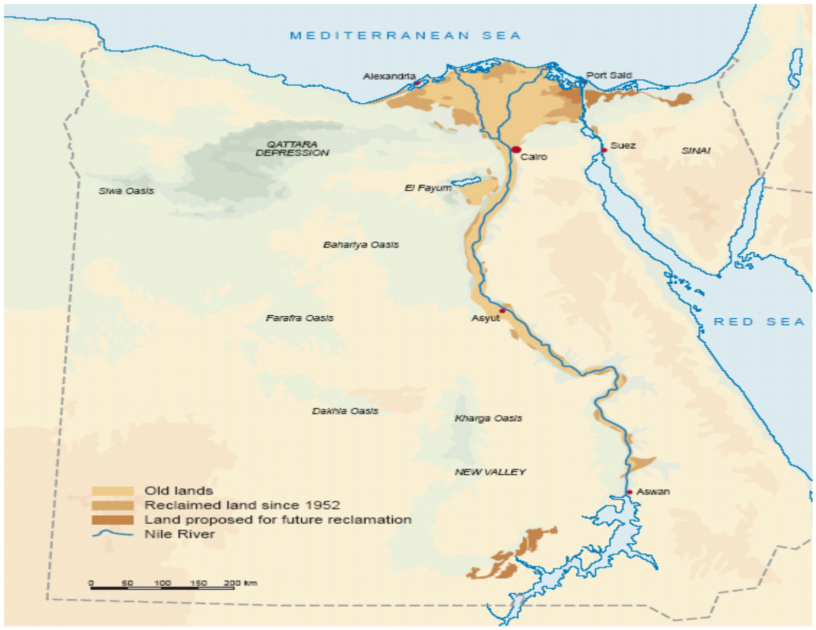


Figure 1. Agricultural land in Egypt

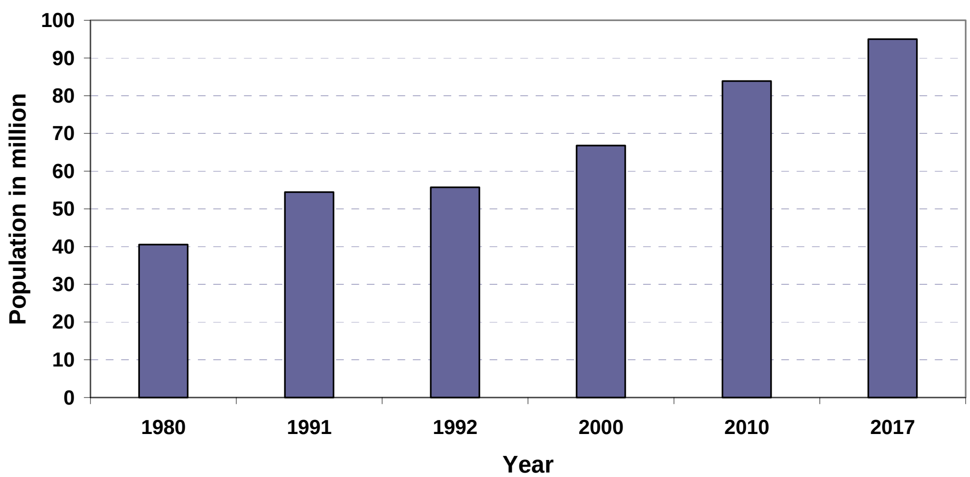


Figure 2. Population growth

The present population of Egypt is strongly concentrated in the Nile Valley and the Delta and 97% of the population lives on 4% of land of Egypt. To relieve the pressure on the Nile Valley and Delta the government has embarked an ambitious programme to increase the inhabited area by means of horizontal and vertical expansion projects in agriculture. All these developments require water and reclamation of both old and new lands. Population Growth and related industrial developments have resulted in a severe pollution of the water either in canals or drains. This pollution is threatening public health and reducing the amount of good quality water either surface or drainage water even further. The government of Egypt has to face these challenges.

Limited Land Resources

The total area of Egypt is 1.001,450 km^2, the majority of which is desert lands representing 96%. Most cultivated lands are located adjacent to the Nile banks, its main branches and canals. Currently the inhabited area is about 12.5 x 10^6 acres and the cultivated agricultural land is about 7.85 x 10^6 acres. The per capita cultivated land declined from about 0.4 acres in 1960 to about 0.2 acres in 1996. The sharp decline of the per capita of both cultivated land and crop area resulted in the decrease of the per capita crop production. This affects directly the food security at the individual, family, community and country levels.

The need for drainage development

In Egypt there is a long history of irrigation. During last decades there has been a development in irrigation in conjunction with the construction of reservoirs. Aside from huge benefits of the irrigation projects they have also resulted in water logging and salinization. Therefore drainage systems are required at a large scale to enable irrigated agriculture on a sustainable basis. It is the role of drainage community to provide policy makers with tools that allow consideration of all aspects regarding production and resources preservation.

The need for drainage is generally determined to increase and/or rationalize food production or to prevent lower production levels due to problems induced by irrigation. In other words there is a direct link between the investments to be made and the benefits to be expected. These benefits generally include the increase in yields or in the case of land reclamation the opening up of new areas resulting in new agriculture production potential. Because of an increase in population and in consumption per head, it is necessary to increase food production. This may be obtained by realizing higher yields at existing agricultural lands and/or reclamation of new land.

Pollution and Environmental Degradation

Although Egypt's efforts in birth control have been acknowledged by the international community, the population still will continue to grow. The population growth has put more stress on both water and land resources. Degradation of these resources, due to heavy socio-economic exploitation, adds up to the water scarcity problem. This situation has brought water quality as a milestone in water resources management. Over the last 30 years applied research has been facilitating the soft shift from water quantity based to water quality based management.

The need for a holistic perspective

No doubt that drainage is an important and complementary part of integrated water resource management and many benefits from drainage are invisible to decision makers, managers, users, stakeholders, private sector and civil society. But in recent years these invisible benefits of drainage have been recognized and the role of drainage went beyond controlling water logging and salinity such as:

- The Economic benefits from drainage include improved crop productivity, greater sustainability, and opportunities for crop diversification for higher income and also from incremental revenues from horticulture or benefits from improved education, health, and family income.
- Social benefits primarily relate to poverty reduction, reduction of mosquito-breeding areas, improved storm water control, and improved access to fields.
- Environmental benefits can include elimination of barren saline areas, and minimizing the movement of chemical and herbicide to drainage water.
- Drainage can improve public health and sanitary conditions in villages, lower maintenance costs of rural roads, enhance the durability of foundations and mud-based houses, and reduce flooding-related infrastructural damage and disruption.

With this new holistic perspective for the benefits from agricultural drainage, a huge potential for investments is available. This new perspective requires a better documentation of the negative and positive impacts of drainage and an assessment of what has worked in the different drainage environments.

POTENTIAL INVESTMENT IN DRAINAGE IN EGYPT

Opportunities for profitable new investments are more difficult because of increasing costs, such as materials, machines, labors, equipments; new environmental and social costs not previously recognized in drainage projects; a growing need for drainage investments; and falling commodity prices. There are, however, significant opportunities for investments in drainage as following:

Investment in public awareness

As mentioned above the role of drainage still invisible for decision makers, managers, users, stakeholders, private sector and civil society. The first step in encouraging the investment in agricultural drainage is to have national public awareness program. The Investment in this program can include preparing television programs, establishing of information centers, organizing workshops and meeting at local and high level, and publishing of newsletters for all communities in the Nation. When the potential benefits from drainage agricultural and the potential investment are known for the hole Nation, the situation will be suitable for creating more drainage projects at different levels.

Investment in existing drainage system utilization

Monitoring and evaluation of existing drainage system is very important for the sustainability of irrigated agricultural to avoid the degradation in soil, crop, and water resources. Adequate financing is essential for such monitoring to correct problems that can be detected. Decisions on when to undertake drainage work require realistic information from baseline studies, projections, or models, especially for newly irrigated land (World Bank 2006).

The expansion of irrigated area slowed from two percent a year in the 1960s and 1970s to hardly one percent in the 1990s, and water is increasingly unavailable for irrigation. Given present land and water resource constraints and the shortage of potential areas for new development, most production gains must come from better utilization of existing irrigated areas (World Bank 2006). This is a great challenge, and for that reason the utilization of existing irrigation and drainage system is a must.

During the last 30-40 years, Egypt has implemented one of the largest drainage networks in the world, which consist of surface drains, subsurface drains, pump stations and other related works. The target area to be provided with subsurface drainage in Egypt is 6.4 million acres and about 5.5 million acres has already been implemented. Subsurface drainage systems in Egypt have reached the stage that more areas installed have, in theory, passed their economic lifetime and these areas need rehabilitation which gives more potential for investments.

Wahba et al 2005 showed a new concept of management for existing subsurface drainage systems in Egypt and a large opportunity for irrigation water can be saved by proper management of these existing systems. For that reason with a low investment in utilization of existing drainage system more benefits can be gained. The investment here includes monitoring and evaluation, management of existing system, development of tools for management, training and public awareness.

Investment in Drainage of the New Lands

The population in Egypt is expected to reach 85 million within two decades. Unemployment runs between 11 to 20 percent of the population. For this reason horizontal expansion is being one of the main policies of the Egyptian Government to provide food, all manner of jobs and long-term investment opportunities for the increasing population. El-Salam project (585,000 acres) and Toshka project (540,000 acres) are examples for the new reclaimed area in Egypt.

The main characteristics of the new lands differ from the old Delta lands with regard to soil and crop types, water quantity and quality and availability, infrastructure, irrigation types, mentality of farmers, users, stakeholders, and economic levels. Based on these differences, the investments in drainage in the new lands will be absolutely different than in old land with regard to source of funds, the way for paying infrastructure, cost recovery, and maintenance service The investment in the new lands may include, infrastructure (open drains, pump stations, drainage structures), water user associations, and water boards, drainage materials, machines and maintenance equipment, consultation work for monitoring and evaluation of water tables, water quality, and soil quality, changes in cropping systems, water supply, seasonal water variation, and environmental assessments,

Investment in drainage of Oasis and closed basins

The New Valley is a large depression located between the Nile Valley and Libya. In this depression there are five main Oasis which are Paris, Kharaga, Dakhla, Farafra and Bahariya.

The future cultivated land will amount to 152,370 acre by year 2010 (Nialnd et al 2005). Also there is Siwa Oasis in the North West of delta with an agricultural area about 30.000 acre. Generally drainage problems are created from excess irrigation water discharged from free flowing springs and uncontrolled wells. This causes increases in subsurface water level and soil salinity of top soil layers

The drainage in such Oasis is not like the conventional system in old land due to the topographic features of the depressions and the investment here will include non-conventional drainage systems, integrated water management, utilization and protection of ground water, utilization of drainage water, multiuse of drainage water, utilization of sunshine power for desalinization of drainage water, and safety disposal of drainage water. In recent years a lot of investors have started reclamation of new lands in these areas and at the same time these Oasis are famous with high value crops like dates and olives which give more potential for higher economic return from drainage investment in these areas.

Investment in Bio-drainage

Bio-drainage has not been used extensively in large-scale projects, although it is promising under the right conditions. Bio-drainage removes excess groundwater through transpiration by vegetation with high water use, such as eucalyptus trees. This maintains groundwater levels below the root zone of crop plants. Other advantages are wind erosion control, elimination of drainage water disposal problems, low investment cost, and ecological benefits. Disadvantages are that bio-drainage areas use potential cropland, do not remove salts, and may interfere with water use by crops (World Bank 2006).

An integrated irrigated system with shelterbelts trees as a bio-drainage in Egypt's South Valley Project is investigated by Amer and Wahba 2005 for enhancing sustainable communities in the area has been proposed and multi benefits with sand dunes fixation have been shown. The proposed system is recommended to be applied in an integrated way with the irrigation and drainage system. Bio-drainage still new in Egypt and with the consideration of potential benefits from it, so investment in bio-drainage can be in the first priority in the future of drainage investment in Egypt.

Investment in Controlled Drainage

Controlled drainage is a technique for regulating the water table level, which allows harvesting “more crop per drop” in both the scheme and the basin. The technique can be part of new drainage systems and retrofitted in existing ones. It is particularly suitable in irrigated regions threatened by water scarcity. Applying controlled drainage will help in regulating drainage and preventing ‘over drainage’. The economic instruments that are advocated to address the overuse of irrigation water have their equivalents in drainage, but again there is a need to build up a critical mass of knowledge in this field.

In response to rising water tables in the Nile Delta, a free-flowing subsurface drainage system has been installed across most of the agricultural sector of the Nile Delta. Recent controlled drainage pilots in rice growing areas showed water savings of up to 40 percent (DRI 1998). Research work was done in small field plots planted to corn and wheat. Farmers can recoup the costs of controlled drainage in two or three seasons, owing to increased crop yield. In circumstances where high water savings can be achieved, the internal rate of return is 100 percent, meaning that the investment is recouped within one year (Abbott et al. 2001; Abdel-Gawad 2002).

The results from an experimental field to investigate the effects of controlled drainage on the quality of subsurface drainage outflows in Egypt showed the potential environmental and economic benefits with the application of controlled drainage in semi-arid regions (Wahba et al 2001).

North America and Northern Europe have invested millions of dollars in research and development on controlled drainage to combat non-point source pollution by nitrates. The field scale results were quite rewarding through reduced drainage flows and pollutant loads, and increased crop yield (World Bank, 2005). Controlled drainage with it's huge benefits for old and new subsurface drainage system will be in the main drainage investments agenda in Egypt

Investment in Capacity Building

A great deal of water is being misused or mismanaged owing to weak institutions and poor water policies. The solution entails taking human and institutional processes and capacities more into account in the design and operation of hydraulic devices and infrastructure. Training and technical assistance are required for building capacity of individuals and institutions, such as local governmental bodies and public sector, board members, WUA personnel, and water staff agencies. Establishing leadership and ownership and building capacity (organizational and managerial skills, and databases) in agricultural water projects, and related reforms of policies and organizational structures, are Important for sustainability of investments.

Investment in water quality

Environmental concerns need to be mainstreamed into all aspects of water management and agricultural policy. Nowadays the deterioration of water quality in the drainage networks in Egypt is a major concern. Almost of villages in rural areas in Egypt do not have access to sanitary system and sewage water from these areas is going direct or indirect to drainage water which affects the quality of this water. More work is needed in the Investment of low cost wastewater treatment, controlling pollution from the source, public and best agricultural management practice. Improving drainage water quality will lead to protecting the public health and this is one of the main investment opportunities for companies and private sector to take into consideration.

Investment in operation and maintenance

Egypt's Ministry of Water Resources and Irrigation, took a successful process approach in which it gradually built support for reform. Egypt's Public Authority for Drainage Projects (EPADP) brought massive and rapid drainage development soon after its establishment, but the way it operates is outdated by today's rapidly changing environment and the mounting costs of operation, maintenance, and replacement.

The O&M plan should be based on an inventory of all the infrastructure work and include an asset management plan defining the frequency of routine maintenance and life of the work. This plan should be the base for assessing the annual maintenance budget. The benefits expected from the above actions for effective O&M include:

- Better drainage service to users
- More benefits can be gained
- Positive impacts on the environment and on saline and water
- Increased life of drainage infrastructure.
- Better utilization of the drainage system

The agency needs to shift from construction to maintenance, tailor designs to users as well as to sites, decentralize water management, and privatize service delivery. There is a need to plan drainage systems in such a way that maintenance is the key element, easy to handle, relatively inexpensive and can be done locally. There is moreover much work to be done in documenting the different options in maintenance and the type of maintenance organization required. All of these are open large area for investment in the operation and maintenance of drainage system.

Investment in GIS and Remote Sensing application

Recent research breakthroughs in remote sensing enable the quantification of water consumption and crop production without agrohydrological ground data. These measurements provide a vehicle for assessing farm management in terms of land productivity, water productivity, irrigation efficiency, environmental degradation, and farmer income (World Bank, 2005).

Drainage issues should be assessed through remote sensing, combined with geographic information system (GIS) and modeling technologies that facilitate applying integrated approaches in drainage system planning and management. These technologies are useful when assessing how drainage interventions will change the natural (agro) hydrological conditions in the resource systems, how the social and environmental values may change, and which benefits and losses may materialize. The application of such techniques in Egypt is still very limited and so there is a great potential of investments in using these technologies the near future.

Investment in drainage water and treated wastewater reuse

Egypt's freshwater supply is constant at 55.5 billion m^3 a year, but the country faces a double challenge. It has to supply water to newly reclaimed areas, which means it has to increase crop production on all new and existing irrigated areas using the same total water supply. For that reason the reuse of agricultural drainage water became national policy in the 1980s, currently, 5 billion m^3 of drainage water, with an average salinity of 1.8 dS/m, is reused each year. The policy of the (MPWRI) is to re-use as much as 7.0 billion cubic maters by the year 2010. The realization of this target depends on the management approaches which ensure safe environmental impact on soil, crop and human health.

Reuse of drainage water holds great potential for saving valuable freshwater resources for competing prime uses that require more stringent water quality standards. It can provide a reliable supply of irrigation water and rich nutrients to cropped fields. Furthermore, reuse may alleviate drainage disposal problems in rivers and streams by reducing the volume of drainage water as well as helping in the restoration of natural wetlands.

To encourage the investment in drainage and wastewater reuse a new policy should be considered to give the private sector a right to water which they can treat.

Role of private sector

A new role for private sector participation is needed. The private sector (farmers labors, small contractor, and stakeholders), can offer a wide range of products and services which can promote sustainable irrigated agriculture. Many poor smallholder farmers and holders of small enterprises do have access to some funds, though limited, and are willing to invest in agricultural activities with the appropriate incentives and investment conditions. Encouragement of such participation requires changes in the direction of efforts by public sector actors and donors. Public sector actors including donors can prime such investments and facilitate the investment process through training, demonstration, information centers, adequate legislation, and setting up institutions to empower farmers and enterprises, quality control of drainage installation, transfer of management of drainage systems to empowered farmers, arranging for credit schemes, among others. Private sector requires an investment climate providing security for investment.

Role of government

Creating an investment climate must be the top priority for governments to promote private sector participation in investments in drainage and integrated water resources management in order to eliminate household food insecurity, rural poverty and achieve economic growth.

The role of government is changing, and investment will be needed to strengthen core government functions, such as: establishing the policy framework within which the private sector can function; regulation of land and water rights and markets; integrated water resources management; environmental protection; research and technology transfer; and rural infrastructure. Governments need also to set an incentive structure that incorporates principles of equity within the context of customary rights and that provides for recovery of operation and maintenance costs as the basis for quality water service and scheme sustainability.

Financing of drainage projects

Drainage projects can either be partly or wholly financed by a government from public funds as part of a public task to improve the production potential and/or to arrest further deterioration of the production potential and environment. The national benefits are expected to be an increase in local and, hence, national income. This can be translated into an improved tax base, better living conditions and perhaps reduced health costs. Private initiatives for construction and financing of large-scale drainage systems are rare. Organizing the financing and recovery of the cost is largely dependent on the national customs and policies. It can range from being completely financed by government funds with the expectation that costs will be recovered through taxes, to being completely financed by the direct beneficiaries, either directly or through loans (Nijland et al 2005). An approach often used is as follows:

- The main infrastructure which include the main surface drains, the outlets and/or pumping stations, is considered a public good and is entirely financed by the government with public funds either directly or though loans. Repayment is eventually expected to come from an increased tax base or payment for maintenance service.
- The on-farm works, which include field drainage systems, are considered to be the direct benefit of the land owner/user. Therefore, the landowners have to finance these works, either fully or partly. Partly, because in some cases government subsidizes these works and expects repayment of their subsidies through additional tax revenues in the future.
- Landowners finance their part with a loan with a commercial loan or a subsidized loan. The repayment conditions of the loans can be made on the basis of projected yield improvements.

CONCLUSIONS

- In spite of the great achievements and benefits of drainage in Egypt, there is a huge potential for investments that are needed to sustain agricultural drainage against the future challenges.
- The potential investments include public awareness, existing drainage system utilization, drainage of the New Lands, drainage of Oasis and closed basins, bio-drainage, controlled drainage, capacity building, drainage water quality, operation and maintenance of drainage system, GIS and Remote Sensing application, and drainage water and treated wastewater reuse.
- A new role for private and governments sector is needed. The private sector can offer a wide range of products and services which can promote agriculture production and growth. To encourage the investment in drainage and wastewater reuse a new policy should considered to give the private sector a right to water which they can treat.
- Creating an investment climate must be the top priority issue for governments to promote private sector participation in investments in drainage.

REFERENCES

Abbott, C., S. Abdel-Gawad, M. S. Wahba, and A. Lo Cascio. 2001. “Field Testing of Controlled Drainage and Verification of CDWaSim Simulation Tool.” HR Report OD/TN102. HR Wallingford, Wallingford, U.K.

Abdel-Dayem, S., H. Hoevenaars, P. Mollinga, W. Scheuman, R. Slootweg, and F. van Steenbergen. 2004. “Reclaiming Drainage: Toward an Integrated Approach.” Agricultural and Rural Development Report 1. World Bank, Agricultural and Rural Development Department, Washington, DC.

Abdel-Dayem, S., H. Hoevenaars, P. Mollinga, W. Scheuman, R. Slootweg, and F. van Steenbergen. 2004. “Reclaiming Drainage: Toward an Integrated Approach.” Agricultural and Rural Development Report 1. World Bank, Agricultural and Rural Development Department, Washington, DC.

Abdel-Gawad, S. 2002. Egyptian-Dutch Co- Operation in Land Drainage and Technology Transfer.” GRID Newsletter 19, 10–11. IPTRID/FAO, Rome.

Ali, A. M., H. M. van Leeuwen, and R. K. Koopmans. 2001. “Benefits of Draining Agricultural Lands in Egypt. Results of Five Years’ Monitoring Drainage Effects and Impacts.” *Water Resources Development* 17(4): 633-646.

Amer, M. H and Wahba, M.A.S. 2006. Sand Dune Fixation Towards Desertification Control in Toshka Project, South Valley of Egypt. International Symposium on Water and Land Management for Sustainable Irrigated Agriculture. Adana-Turkey 4 - 8 April, 2006.

DRI (Drainage Research Institute). 1998. “Controlled Drainage through Water Users Associations.” DRI Technical Report 102. Ministry of Water Resources and Irrigation (MWRI) Drainage Research Institute, Cairo.

IWMI (International Water Management Institute). 2004. Review of literature report. Volum1-highlights of finding of various components in Draft final report on Investment in agricultural water management in Sub-Saharan Africa: Diagnoses of trend and opportunities. Submitted to The African Development Bank.

Nijland, H.J., Croon F.W. and Ritzema H.P., 2005. Subsurface Drainage Practices: Guidelines for the implementation, operation and maintenance of subsurface pipe drainage systems. Wageningen, Alterra, ILRI Publication no. 60, pp. 608.

Wahba, M.A .S, El-Ganyny, M, Abdel-Dayem, M S, Goubran, A and Kandil, H. 2001. Controlled Drainage effects on water quality under Semi-Arid conditions in Westeen Delta of Egypt. Irrig and Drain. 50: 295-308.

Wahba, M.A.S, Christen, E and Amer, M. H. Irrigation Water Saving by Management of Existing Subsurface Drainage in Egypt**.** Irrig and Drain. 54: 1-11 (2005).

World Bank. 2002. "Implementing the New Rural Development Strategy in a Country Driven Process: Agriculture and Rural Development Project Profiles." Presentation at the Country Director/Rural Sector Board Learning Event, September 8-10, sponsored by the World Bank, Antalya, Turkey.

World Bank. 2003. *Reaching the Rural Poor: A Renewed Strategy for Rural Development*. Washington, DC: World Bank.

World Bank. 2004. Country Case Studies on Drainage in Bangladesh, Egypt, Indonesia, Mexico, Pakistan, and the Netherlands. *Toward Multidisciplinary and Integrated Agricultural Drainage*. Washington, DC: World Bank, Agriculture and Rural Development Department.

World Bank. 2005. Shaping the Future of Water for Agriculture. Investment note 3.6. *A Sourcebook for Investment in Agricultural Water Management*.

World Bank. 2006. Agriculture Investment Source book. www.worldbank.org/agsourcebook.

EAST SAN JOAQUIN WATER QUALITY FRAMEWORK: THE APPROACH

L.S. Hunt[1]
W. Ward[2]
J. Edmunds[3]
T. Cooke[4]

ABSTRACT

The East San Joaquin Water Quality Framework, funded by California Proposition 13 Drinking Water Program funds, was created to provide a watershed organizational structure for cooperative and coordinated water quality improvement activities. The Framework study area encompasses approximately 600,000 acres in the California San Joaquin Valley, including areas served by five irrigation districts: Oakdale, South San Joaquin, Modesto, Turlock, and Merced. Work conducted under the Framework includes water quality monitoring, best management practices and implementation activities, and education and outreach to the urban and agricultural communities. In order to focus the 2006 monitoring program, a comprehensive analysis was undertaken using 2000-2005 water quality monitoring data collected by state, federal and local agencies, cities and counties, National Pollutant Discharge Elimination System (NPDES) permittees, irrigation districts, water quality coalitions, universities and other entities. The analysis includes spatially explicit pesticide use data, land use information, and detailed watershed mapping. The historical data analysis and the 2006 data provide insight into the nature of the water quality issues and assists in developing specific recommendations for management practices and implementation strategies in the Framework area. Water quality constituents that are consistently elevated in the area include organophosphate pesticides such as diazinon and chlorpyrifos, herbicides such as diuron, and inorganics such as copper, lead and zinc. In addition, several other pesticides have been detected in surface waters at levels exceeding screening thresholds, including carbaryl, malathion, simazine, diuron, oryzalin, and azinphos-methyl.

INTRODUCTION AND BACKGROUND

The East San Joaquin Water Quality Framework provides a cost-effective watershed organizational structure for cooperative and coordinated water quality improvement activities. This structure helps to facilitate decisions on how to attain water quality

objectives for the San Joaquin River eastside tributaries, and manage loads entering the San Joaquin River to protect water quality in the Bay-Delta. The Framework study area is located in

[1] Senior Environmental Engineer; URS Corporation, 1333 Broadway, Oakland CA 94612; lisa_hunt@urscorp.com.

[2] Assistant General Manager – Water Operations; Modesto Irrigation District, P.O. Box 4060, Modesto, CA 95352; walterw@mid.org.

[3] Senior Environmental Scientist; URS Corporation, 1333 Broadway, Oakland CA 94612; jody_edmunds@urscorp.com.

[4] Manager – Water Environment Department; URS Corporation, 1333 Broadway, Oakland CA 94612; terry_cooke@urscorp.com.

the San Joaquin Valley on the east side of the San Joaquin River. The major tributaries that transect the area are the Merced, Tuolumne, and Stanislaus Rivers, the combination of which deliver an average of 66 percent of the San Joaquin River's annual flow (Domagalski and Munday 2003). The study area encompasses approximately 600,000 acres, including areas served by five irrigation districts: Turlock, Modesto, South San Joaquin, Merced, and Oakdale (see Figure 1).

The climate of the San Joaquin Valley is Mediterranean with hot, dry summers and mild, rainy winters. The total annual precipitation is approximately 12 inches, with most precipitation occurring between November and March. The summer high mean temperature is about 91 degrees Fahrenheit, and the winter mean temperature is about 40 degrees Fahrenheit. Land use is dominated by agriculture, which is dependent upon the water districts for distribution of water during the annual irrigation season. The normal irrigation season extends from March to late October or early November. Peak irrigation water use occurs in July. In addition to various agricultural land uses, some urban and suburban developments within the study area have experienced growth in recent years.

The top 5 revenue-producing agricultural commodities in the three-county area that the Framework resides within are shown in Table 1.

Table 1. Top 5 Revenue-Producing Commodities in Merced, San Joaquin, and Stanislaus Counties

Commodity	**Value ($MIL)**
Milk	1,235
Almonds	578
Chickens	367
Cattle	211
Tomatoes	199

Source: NASS-CA 2004

Multiple water quality issues are currently being addressed in the San Joaquin River and its tributaries under various programs. Section 303(d) of the Federal Clean Water Act requires states to identify and include on the 303(d) list water bodies for which beneficial use is threatened or impaired due to failure to meet water quality standards. A Total Maximum Daily Load (TMDL) is defined as the maximum amount of a pollutant that a water body can receive and still meet water quality standards and maintain designated beneficial uses. A TMDL is implemented by specifying how much of that pollutant can come from point, nonpoint, and natural sources and by carrying out a plan to reduce the releases from these sources. The TMDL calculation must include a margin of safety and also account for seasonal variations. Listing a stream segment on the 303(d) list requires that a TMDL analysis be completed to address the pollutant(s) of concern in the watershed.

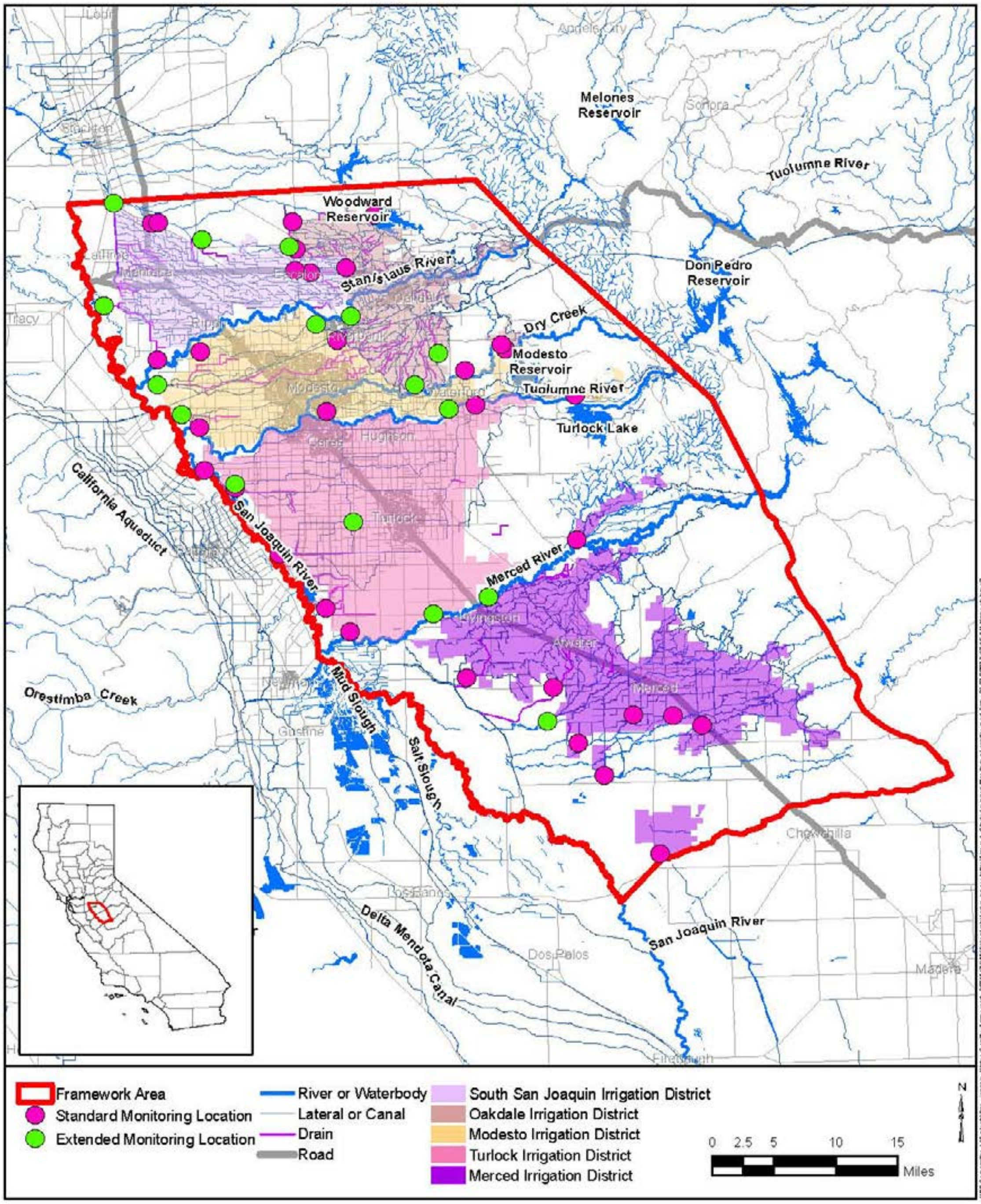


Figure 1. Framework Study Area and Monitoring Locations

Currently, the state has focused TMDL resources in the San Joaquin River Basin on the water quality problems it considers most significant:

- Salinity and boron (adopted TMDL for the lower San Joaquin River (downstream of Mendota Dam, upstream of Vernalis, including tributaries to the river), TMDL in development upstream)
- Selenium (adopted TMDL)
- Pesticides (adopted TMDL for chlorpyrifos and diazinon for the lower San Joaquin River)
- Dissolved oxygen (adopted TMDL)
- Mercury (due mainly to historical mining impacts)
- Nutrients

In 2003, the Central Valley Regional Water Quality Control Board (CVRWQCB) adopted new requirements for water quality monitoring of agricultural runoff under the Irrigation Lands Program. Previously, irrigation return flows and storm water runoff from agricultural land were granted an exemption from the NPDES permit program by the CVRWQCB. In 1999, Senate Bill 390 was adopted, changing the requirements for authorizing waivers, and the interim Conditional Waiver was adopted by the Regional Board in 2003. This interim waiver focuses on starting data collection, which will be the foundation of a longer-term program. Under the requirements, dischargers must accomplish the following:

- Assess the impacts of waste discharges from irrigated lands to surface waters
- Determine the degree of implementation of management practices to reduce discharge of specific wastes that impact water quality
- Determine the effectiveness of management practices and strategies to reduce discharge of specific wastes that impact water quality
- Determine the concentration and load of waste in these discharges to surface waters
- Evaluate compliance with existing narrative and numeric water quality objectives (WQOs) to determine if additional implementation of management practices is necessary to improve and/or protect water quality

The goal of the Framework is to develop and implement a comprehensive program that accomplishes the following:

- Supports compliance with the Irrigated Lands Program requirements (required by the CVRWQCB since 2003)
- Supports data collection and implementation activities for TMDL projects currently under way
- Provides for development of data on potential water quality problem areas

- Provides information to begin to differentiate among sources (agricultural, urban, dairies, etc.) and focus future monitoring efforts
- Provides data on effectiveness of management practices and other control actions

In addition to a consolidated water quality monitoring program, Framework activities include evaluation and promotion of management practices that will result in improvements to water quality, as well as general outreach and education regarding water quality issues.

ORGANIZATIONAL STRUCTURE

The organizational structure of the Framework is shown on Figure 2. The Water Quality Management Committee is the decision-making body shown in the center of the diagram and is composed of managerial representatives from the San Joaquin River Group Authority and each of the five irrigation districts.

Water Quality Technical Committee members were selected based on expertise in hydrology, water quality, irrigation practices, agricultural practices, urban/industrial practices, and outreach and include representatives from irrigation districts; farm bureaus; county agricultural commissioners; resource conservation districts; cities and counties; consulting firms; and state and local agencies. Responsibilities of the Water Quality Technical Committee include:

- Exchanging technical information among the participants
- Coordinating and reviewing regional monitoring activities
- Collaborating with state and federal monitoring programs to coordinate, interpret, and report on the data collected to adaptively manage the water quality implementation plans
- Providing guidance for the development of management measures tailored to varied crops and farming practices in the Framework study area
- Providing guidance for the development of a comprehensive outreach and education program associated with point-source and nonpoint-source water quality and the implementation of management measures
- Overseeing the development and implementation of a tracking and reporting system for management practices and effectiveness

As shown on Figure 2, Framework outreach activities are carried out with the help of the organizations represented as the “spokes.” Many of these organizations have outreach programs of some type already in place, and the Framework supplements existing programs. Through these “spokes,” education and outreach related to water quality pollution prevention is disseminated to the agricultural and urban dischargers, as well as others whose activities may affect regional water quality. This structure is also being used to disseminate information on results of water quality and management practice effectiveness studies conducted under the Framework and other related programs.

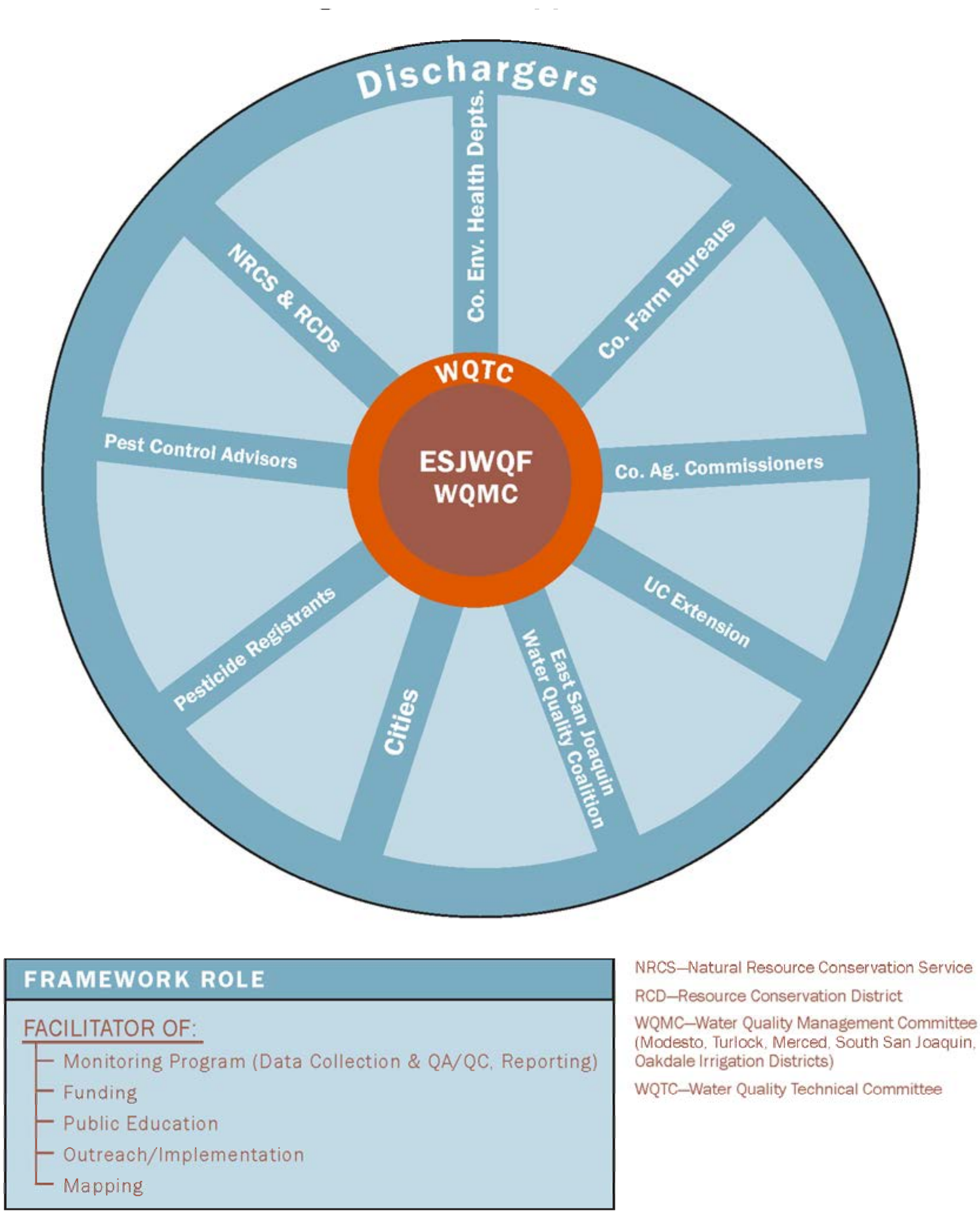


Figure 2. East San Joaquin Water Quality Framework Organizational Approach

OUTREACH AND EDUCATION

The goal of the outreach and education program is to increase public awareness about water quality issues and pollution prevention measures. Specific outreach and education objectives include:

- Improving the understanding of regional stakeholders about the potential impacts that certain practices can have on local and regional water sources
- Providing stakeholders with current information about management practices with the potential to minimize the effects of agricultural and urban drainage on local and regional water sources
- Informing stakeholders of the potential consequences of not meeting water quality targets
- Increasing the interaction and exchange of information between the scientific community and stakeholders on management practices and water quality issues

The Outreach Plan was developed in two phases. The first phase involved the collection and analysis of critical background information. This research involved reviewing existing documents, outreach tools, and procedures and conducting a series of interviews with key stakeholders. The results of this work provided:

- Identification of target audiences and existing outreach efforts
- Information on how stakeholders understand the Framework and its purposes
- Insight into stakeholder expectations for the Framework
- Recommendations on filling potential information gaps, taking advantage of outreach opportunities, and bringing in audiences not currently receiving information through existing outreach activities

The second phase of the Outreach Plan involved the development of an implementation strategy for effectively disseminating outreach information based on the results of the first phase. The Outreach Program includes tasks designed to feed into the various sections of the Framework where communication with stakeholders is most useful. The Framework relies in large part on existing outreach efforts, building rather than replacing work accomplished by local and regional entities.

Outreach tasks accomplished by the Framework include:

- Developed a website to educate the public about water quality issues in the region and actions they can take to protect water quality. Include a “members only” section for review of draft documents, water quality data, and meeting information.
- Conducted a survey of growers and pest control advisors focused on information pertaining to pesticide use and management practices utilized in the Framework area.

- Presented results of water quality monitoring and pilot studies focused on reducing pesticide movement into surface water at several meetings and conferences targeting the agricultural, scientific and regulatory communities.

MANAGEMENT PRACTICE IMPLEMENTATION

The goal of the Management Practice Implementation Program is to increase the understanding of the management practices available, thereby encouraging the use of the most effective management measures and hopefully reducing loads of pollutants of concern to surface water bodies. Specific tasks include:

- Review and evaluate current and proposed management practices used within the Framework study area to reduce impact to water quality
- Develop and manage a communication network among entities performing research on management practices relevant to the Framework study area
- Determine additional research needs for management practices, including developing effectiveness data on management practices
- Evaluate the effectiveness of current management practices using implementation tracking and water quality monitoring data
- Identify new management practices for irrigation district activities (and other stakeholders), and prepare written guidance if needed
- Establish and manage a structure for funding management practice implementation by growers or other stakeholders in the Framework study area

Based on the needs identified by this process, the Framework has funded and carried out two pilot studies focusing on reducing the transport of pesticides to surface waters within the Framework area (Blankinship et al. 2007).

HISTORICAL DATA EVALUATION

Historical data from within and surrounding the Framework area were compiled for the years 2000 to 2005. Several types of data, including water quality, flow, precipitation, pesticide use, and land use data, were collected for this study. The data were collected from government agencies, coalition groups, irrigation districts, universities, government web sites, existing water quality databases and scientific papers. Precipitation data were downloaded from the California Irrigation Management Information System Web site. Land use data were obtained from the Multi-Resolution Land Characteristics Consortium National Land Cover Dataset (compiled from 1992 Landsat Imagery and updated based on 2000 data). To help identify correlations between pesticide use and pesticides detected in waterways in the Framework area, Pesticide Use Reports (PURs) were obtained from the California Department of Pesticide Regulation Web site. PURs contain data on agricultural pesticide use, including date and location where the application was made, the quantity and type of pesticide used, the site identification number, and the pesticide user. If the pesticide was applied to a crop, the type of crop is specified. The PURs also contain data on pesticide applications to parks, golf courses, cemeteries, rangeland, pastures, and along roadway and railroad rights-of-way.

The data were compiled and reviewed to identify the following:

- Water quality parameters with concentrations above screening thresholds
- Spatial trends in elevated parameters
- Temporal trends in elevated parameters
- Correlations between elevated parameters and land use
- Correlations between elevated parameters and pesticide use

The database of historical surface water quality data for 2000–2005 included 398 parameters that were measured in the Framework area and 224 parameters that were measured at stations on the main stem of the San Joaquin River. Because of the large number of parameters, it was impractical to conduct a detailed spatial and temporal evaluation of each parameter. Therefore, a systematic process was developed to separate the parameters into various categories, and select certain parameters for further evaluation based on potential for water quality impacts.

The first phase of the data evaluation was to identify constituents in the database that exceeded initial screening thresholds (ISTs). ISTs were identified based on the health and survival of freshwater aquatic life as well as protection of drinking water and other water uses. The screening thresholds include both regulatory WQOs, and nonregulatory guidance values or toxicity thresholds. The most conservative values were selected as ISTs solely for purposes of initial screening. A concentration greater than an IST does not necessarily indicate a water quality problem, it merely indicates that further evaluation may be necessary. For those parameters found to occur at concentrations above the ISTs, an evaluation of the appropriateness of the IST was conducted.

For many parameters the datasets were not adequate to determine whether concentrations were above the ISTs within the Framework area, possibly due to one of more of the following factors:

- Insufficient number of datapoints to adequately represent typical conditions
- Insufficient number of stations for adequate spatial characterization
- Insufficient datapoints for certain months of year to adequately represent seasonal variability
- Reporting limits often above ISTs, preventing comparison of concentrations to ISTs for nondetect samples
- No IST available

In summary, the objectives of the initial screening process were to:

- Determine whether the dataset for each parameter is adequate to draw any conclusions regarding potential for water quality impacts

- Identify analytes that may be considered minor or insignificant regarding their potential impact on water quality (consistently below ISTs)
- Identify analytes that may have the potential to be associated with adverse effects on water quality

Table 2 summarizes the statistics on parameters that were found to have adequate data sets for evaluation within the Framework area, and were measured in concentrations above ISTs. Most of these parameters are being evaluated in more detail under the Framework.

MONITORING PROGRAM

The goals of the monitoring program include identification and evaluation of the following:

- Parameters that occur in concentrations above ISTs
- Potential sources, causes, and impacts of elevated concentrations of parameters
- The degree of implementation of management measures for improving water quality
- The effectiveness of management practices and strategies

Monitoring conducted under the Framework will assist the irrigation districts in meeting the requirements of the Irrigated Lands Program, assist the CVRWQCB in developing and implementing current and scheduled TMDLs for the San Joaquin River, and create a structure for future monitoring in the Framework study area. This approach includes working with the CVRWQCB on quantitative assessments of pollutants that may cause water quality impairments, determining specified amounts and causes of a particular pollutant that may be present in a water body, determining appropriate allocations of allowable pollutant loads among sources, and coordinating and refining monitoring programs within the San Joaquin River eastside tributary subwatersheds.

Forty-eight water quality monitoring sites were chosen within the Framework study area to (1) represent discharge affected by a variety of land use areas, (2) represent and capture the majority of the outflow leaving each irrigation district, (3) integrate the various monitoring projects currently under way within the Framework study, and (4) characterize inflows into each irrigation district. Monitoring sites are shown in Figure 1.

Monitoring began in December 2005 and continued through the 2006 irrigation season. Two storm events were targeted during the nonirrigation season, and storm samples were collected at a subset of 16 sites that capture the most storm water runoff and are accessible during a storm. Discrete samples were taken during the storm event and then also two days after the storm event, as required for the Ag Waiver program. Monitoring was conducted twice a month during the irrigation season. Due to budget constraints, not all parameters could be analyzed during all 10 irrigation season events.

Table 2. Analytes with Adequate Data for Evaluation, Some or All Samples in Framework Area Exceeding ISTs (2000-2005)

			Screening Criteria		**Sample Size and Detection Rate**					
Total / Dissolved	**Analyte**	**Unit**	**Initial Screening Threshold (IST)**	**Basis of IST**	**Number of Samples**	**Number of Stations**	**Detection Rate**	**Mean**	**Max Detected**	**IST Exceed-ance Freq**
Total	*E.Coli*	MPN/100 ml	126	Central Valley Regional Board 5 – Basin Plan	572	38	99%	593	24000	**53%**
Total	Total Coliform	MPN/100 ml	240	Central Valley Regional Board 2 – Basin Plan	1076	26	60%	1597	160000	**44%**
Dissolved	Dissolved Organic Carbon	mg/L	3	CALFED Water Quality Program (WQP) Record of Decision (ROD) Target	164	22	100%	4.28	19.6	**40%**
Total	Bromide	mg/L	0.05	CALFED WQP ROD Target	24	12	6%	0.321	1.8	**8%**
Total	Chloride	mg/L	230	U.S. Environmental Protection Agency (USEPA) National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	176	29	98%	22.4	250	**0.6%**
Total	Conduc-tivity	µS/cm	700	Basin Plan Water Quality Objectives for Inland Surface Waters	6985	98	100%	191	125281.9	**2%**
Total	Total Alkalinity	mg/L	<20	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	132	17	100%	110	460	**3%**
Total	Total Dissolved Solids	mg/L	450	Agricultural Water Quality Limit	433	64	99%	264	1600	**22%**

Table 2. Analytes with Adequate Data for Evaluation, Some or All Samples in Framework Area Exceeding ISTs (2000-2005)

			Screening Criteria		Sample Size and Detection Rate					
Total / Dissolved	**Analyte**	**Unit**	**Initial Screening Threshold (IST)**	**Basis of IST**	**Number of Samples**	**Number of Stations**	**Detection Rate**	**Mean**	**Max Detected**	**IST Exceed-ance Freq**
Total	Total Organic Carbon	mg/L	3	CALFED WQP ROD Target	638	82	98%	7.85	120	**64%**
Total	Diuron	µg/L	10	USEPA Drinking Water Health Advisories or Suggested No-Adverse-Response Levels for toxicity other than cancer risk	184	40	30%	9.08	860	**5%**
Total	Oryzalin	µg/L	35	USEPA Integrated Risk Information System Reference	83	16	6%	3.29	170	**2%**
Dissolved	Manganese	mg/L	0.05	Drinking Water Standards (California & Federal) Maximum Contaminant Levels (MCLs)	105	11	100%	0.0195	0.115	**5%**
Dissolved	Sodium	mg/L	20	USEPA Drinking Water Health Advisories or Suggested No-Adverse-Response Levels for toxicity other than cancer risk	105	11	100%	16.5	139	**20%**
Total	Arsenic	mg/L	0.01	Drinking Water Standards USEPA Primary MCL	212	31	41%	0.00224	0.0101	**0.5%**
Total	Boron	mg/L	0.8	Basin Plan Water Quality Objectives for Inland Surface Waters	279	26	39%	14.3	516	**13%**
Total	Cadmium	mg/L	0.00052	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life	199	30	22%	6.63E-05	0.00056	**0.5%**

Table 2. Analytes with Adequate Data for Evaluation, Some or All Samples in Framework Area Exceeding ISTs (2000-2005)

			Screening Criteria		**Sample Size and Detection Rate**					
Total / Dissolved	**Analyte**	**Unit**	**Initial Screening Threshold (IST)**	**Basis of IST**	**Number of Samples**	**Number of Stations**	**Detection Rate**	**Mean**	**Max Detected**	**IST Exceed-ance Freq**
				Protection						
Total	Copper	mg/L	0.0029	California Toxics Rule Criteria (USEPA) for Inland Surface Waters, Freshwater Aquatic Life Protection	291	42	83%	0.00517	0.089	**44%**
Total	Lead	mg/L	0.00054	California Toxics Rule Criteria (USEPA) for Inland Surface Waters, Freshwater Aquatic Life Protection	276	32	26%	0.00244	0.039	**13%**
Total	Zinc	mg/L	0.037	California Toxics Rule Criteria (USEPA) for Inland Surface Waters, Freshwater Aquatic Life Protection	295	42	66%	0.588	170	**4%**
Dissolved	Ammonia as N	mg/L	0.179	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	159	16	61%	0.344	10.5	**29%**
Dissolved	Nitrate + Nitrite as N	mg/L	10	Drinking Water Standards USEPA Primary MCL	159	16	99%	2.13	18.7	**2%**
Dissolved	Nitrite as N	mg/L	1	Drinking Water Standards (California & Federal) MCLs	159	16	92%	0.0761	1.69	**1%**
Dissolved	Phosphorus as P	mg/L	0.025	USEPA National Recommended Ambient Water Quality Criteria for Fresh-water Aquatic Life Protection	370	21	98%	0.127	2.58	**84%**

Table 2. Analytes with Adequate Data for Evaluation, Some or All Samples in Framework Area Exceeding ISTs (2000-2005)

			Screening Criteria		**Sample Size and Detection Rate**					
Total / Dissolved	**Analyte**	**Unit**	**Initial Screening Threshold (IST)**	**Basis of IST**	**Number of Samples**	**Number of Stations**	**Detection Rate**	**Mean**	**Max Detected**	**IST Exceed-ance Freq**
Total	Ammonia as N	mg/L	0.179	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	494	22	77%	0.352	14	**15%**
Total	Nitrate as N	mg/L	10	Drinking Water Standards USEPA Primary MCL	501	24	99%	1.73	80	**1%**
Total	Phosphorus as P	mg/L	0.025	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	580	49	92%	0.407	12	**90%**
Dissolved	HCH, gamma	µg/L	0.08	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	256	11	3%	0.00321	0.219	**0.4%**
Dissolved	Chlor-pyrifos	µg/L	0.015	Proposed TMDL	308	16	63%	0.0115	0.3	**12%**
Dissolved	Diazinon	µg/L	0.1	Proposed TMDL	308	16	64%	0.0283	0.947	**5%**
Total	Azinphos methyl	µg/L	0.01	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	715	39	0.8%	0.0391	0.07	**0.8%**
Total	Chlor-pyrifos	µg/L	0.015	Proposed TMDL	574	52	29%	0.0146	0.453	**10%**
Total	Diazinon	µg/L	0.1	Proposed TMDL	574	52	21%	0.0302	0.728	**5%**

Table 2. Analytes with Adequate Data for Evaluation, Some or All Samples in Framework Area Exceeding ISTs (2000-2005)

			Screening Criteria		Sample Size and Detection Rate					
Total / Dissolved	**Analyte**	**Unit**	**Initial Screening Threshold (IST)**	**Basis of IST**	**Number of Samples**	**Number of Stations**	**Detection Rate**	**Mean**	**Max Detected**	**IST Exceed-ance Freq**
Total	Malathion	µg/L	0.1	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	123	24	2%	0.0408	0.4	**0.8%**
Dissolved	Dissolved Oxygen	mg/L	<8	Basin Plan Water Quality Objectives for Inland Surface Waters	3703	82	100%	10.1	631	**21%**
Total	pH	pH units	6.5 - 8.5	Basin Plan Water Quality Objectives for Inland Surface Waters and Drinking Water Standards (California & Federal) MCLs	2738	91	100%	7.40	9.7	**4%**
Total	Turbidity	NTU	50	CALFED WQP ROD Target	1212	82	85%	18.4	698	**8%**
Total	Cypermethrin, total	µg/L	0.002	USEPA National Recommended Ambient Water Quality Criteria for Freshwater Aquatic Life Protection	434	42	0.2%	0.0737	0.03	**0.2%**
Dissolved	Simazine	µg/L	4	Drinking Water Standards (California & Federal) MCLs	308	16	85%	1.80	64.5	**8%**

Therefore, parameters were split into two types: “standard” parameters to be measured at all storm and irrigation season sampling events and at all locations where monitoring occurs (16 during storm season and 48 during irrigation season); and “extended” parameters to be measured at all storm season events at all of the 16 storm season locations, and at 2 irrigation season events at the same 16 locations.

The standard list of parameters includes many of the parameters currently being analyzed under the Ag Waiver requirements, as well as some constituents analyzed under the dissolved oxygen TMDL Upstream Monitoring Program. An extended list of parameters has also been developed that would be analyzed in conjunction with the standard list of parameters on a less frequent basis. The extended list includes acute water column and sediment toxicity testing, metals, and pesticides. The toxicity test methods specified are those that are currently required under the Ag Waiver.

Specific pesticides were chosen for the extended parameter list because (1) they are currently being monitored by a majority of the irrigation districts; (2) they are currently being monitored by the Coalitions; or (3) they are heavily used in the region based on California Department of Pesticide Regulation’s data. Certain pesticides that are heavily used are not proposed for monitoring because no WQOs exist and/or they generally do not present water quality problems (examples include sulfur and metam-sodium). Copper was selected because copper is a constituent in many herbicides used frequently in the region (both terrestrial and aquatic). Copper is also a constituent often found in urban storm water. Zinc was also included because it is typically found in storm water and may be used to help determine the source of pollutants.

The following acute and chronic toxicity testing was conducted at extended sampling locations:

- *C. dubia* (water column acute toxicity) – invertebrate
- *P. promelas* (water column acute toxicity) – fathead minnow larvae
- *Selenastrum capriconutum* (water column chronic toxicity) – algae
- *H. azteca* (sediment toxicity) – invertebrate

Table 3 presents the standard and extended lists of monitoring parameters analyzed under the Framework. Results of the 2005–2007 monitoring are described in separate papers (Edmunds et al. 2007; Cooke et al. 2007).

Table 3. List of Sampling Parameters

Parameters	Method	Framework Standard List	Framework Extended List
General Chemistry			
Flow	Field	●	●
Dissolved Oxygen	Field	●	●
pH	Field	●	●
Temperature	Field	●	●
Electrical Conductivity	Field	●	●
TOC	SM 5301C/ SW846 9060	●	●
Dissolved Organic Carbon	9060	●	●
Turbidity	180.1/SM 2130B and/or Field	●	●
Total Suspended Solids (TSS)	160.2	●	●
Total Dissolved Solids (TDS)	160.1/SM 2540C	●	●
Potassium	200.7/6010B	●	●
Bromide	300.0/320.1	●	●
Total Kjeldahl Nitrogen (TKN)	351.2/351.4	●	●
Nitrate/Nitrite (or Nitrate)	USEPA 353.2 (or 300.0/SM 4500 NO3)	●	●
Total Phosphorous	365.2	●	●
Dissolved Phosphate	365.1/365.2		●
Total Copper	200.7/6010B		●
Dissolved Copper	USEPA 3005, 6010B		●
Selenium	200.7/6010B		●
Total Zinc	200.7/6010B		●
Dissolved Zinc	USEPA 3005, 6010B		●
Hardness	USEPA 132.2		●
Pesticides			
Diazinon	8141		●
Chlorpyrifos	8141		●
Glyphosate (Rodeo, Aquamaster, Roundup-Pro)	547		●
Diuron (Direx, Diuron, Krovar)	632 mod/ 8321A		●

Table 3. List of Sampling Parameters

Parameters	**Method**	**Framework Standard List**	**Framework Extended List**
1,3-dichloropropene	502.1/502.2/ 524.1/524.2		●
Pendimethalin (Pendulum)	8141A mod		●
Triclopyr (Garlon)	8151A mod		●
Cypermethrin Technical 40.0% (Demon WP)	8081A mod		●
Lambda cyhalothrin	1660 mod		●
Esfenvalerate	1660 mod		●
Permethrim	1660 mod		●
Toxicity			
Water Column			
C. dubia (acute toxicity)	a		●
Pimephales. promelas (acute toxicity)	a		●
Selenastrum capriconutum (96 hour)	b		●
Sediment			
H. azteca	c		●
Phase I Toxicity Identification Evaluation (TIE)	d		●

[a] Methods for measuring the acute toxicity of effluents and receiving waters to freshwater and marine organisms. USEPA Office of Water. EPA-821-R-02-012.
[b] Short Term Methods for estimating the chronic toxicity of effluents and receiving waters to freshwater organisms. USEPA Office of Water. EPA-821-R-02-013.
c Methods for measuring the toxicity and bioaccumulation of sediment-associated contaminants with freshwater organisms. USEPA Office of Research and Development. EPA-600-R-99-064.
d Methods for Aquatic Toxicity Identification Evaluations. Phase I Toxicity Characterization Procedures. Office of Research and Development, Duluth, MN. EPA-600-3-88-034.

REFERENCES

Blankinship, M.S., L.S. Hunt, J. Edmunds, T. Cooke, W. Ward. 2007. *East San Joaquin Water Quality Framework: Focused Management Practice Pilot Studies for Prevention of Pesticide Transport to Surface Water.* United States Fourth Annual Conference on Irrigation and Drainage, September 30 – October 6.

Cooke, T., L.S. Hunt, J. Edmunds, W. Ward. 2007. *East San Joaquin Water Quality Framework: Urban Water Quality Issues in an Agricultural Region.* United States Fourth Annual Conference on Irrigation and Drainage, September 30 – October 6.

Domagalski, J.L., and C. Munday. 2003. *Evaluation of Diazinon and Chlorpyrifos Concentrations and Loads, and Other Pesticide Concentrations, at Selected Sites in the San*

Joaquin Valley, California, April to August, 2001. Water-Resources Investigations Report 03-4088. U.S. Department of the Interior, U.S. Geological Survey, Sacramento, CA. Prepared in cooperation with the California Department of Pesticide Regulation.

Edmunds, J., L.S. Hunt, T. Cooke, W. Ward. 2007. *East San Joaquin Water Quality Framework: 2005/2006 Water Quality Monitoring Results.* United States Fourth Annual Conference on Irrigation and Drainage, September 30 – October 6.

EAST SAN JOAQUIN WATER QUALITY FRAMEWORK 2005/2006 WATER QUALITY MONITORING RESULTS

Jody Edmunds[1]
Lisa S. Hunt[2]
Terry Cooke[3]
Walter Ward[4]

ABSTRACT

Surface water quality was measured in irrigation supply and drainage canals in the East San Joaquin Valley as a part of the East San Joaquin Water Quality Framework during and after 2 storm events in December 2005 and February/March 2006, and twice during the irrigation season in June and August 2006. Parameters measured included 11 organophosphate pesticides, 4 pyrethroid insecticides, 6 herbicides, and 3 metals, as well as nutrients and general water quality parameters such as TDS, pH and temperature. Concentrations of all detected parameters were compared to conservative screening thresholds based on ecotoxicity, human health, or agricultural standards. During the stormwater season, diazinon was detected in 28% of stormwater samples, with 16% of the samples exceeding the screening threshold (based on the lowest TMDL objective for chronic toxicity). No diazinon was detected in surface water during the irrigation season. This is consistent with pesticide use trends in the region, as diazinon is primarily used as a dormant spray during the winter. In contrast, chlorpyrifos was detected in 13% of the samples during the irrigation season but only 2% of samples during the storm season, again consistent with pesticide use trends as the highest use of chlorpyrifos occurs during the summer. One other OP pesticide (methyl parathion) and one pyrethroid (cypermethrin) were each detected once above the screening thresholds. Diuron was the only herbicide detected above the initial screening threshold. Copper and zinc were detected above screening thresholds at multiple locations during both storm and irrigation seasons, but selenium was never detected above screening thresholds.

INTRODUCTION AND BACKGROUND

The East San Joaquin Framework study area is located on the east side of the San Joaquin River in the northern San Joaquin Valley (Figure 1) and encompasses approximately 600,000 acres served by five irrigation districts: Oakdale, South San Joaquin, Modesto, Turlock, and Merced. The area includes three major San Joaquin River tributaries, the Tuolumne River, the Stanislaus

[1] Senior Environmental Scientist, URS Corporation, 1333 Broadway, Oakland CA 94612; Phone: (510) 874-3009; Fax: (510)874-3268; jody_Edmunds@urscorp.com.
[2] Senior Environmental Engineer, URS Corporation, 1333 Broadway, Oakland CA 94612; Phone: (510) 874-1795; Fax: (510)874-3268; lisa_hunt@urscorp.com.
[3] Project Manager, URS Corporation, 1333 Broadway, Oakland CA 94612; Phone: (510) 874-1736; Fax: (510)874-3268; terry_cooke@urscorp.com.
[4] Assistant General Manager – Water Operations, Modesto Irrigation District, P.O. Box 4060, Modesto, CA 95352; Phone: (209) 526-7459; Fax: 209-526-7352; walterw@mid.org.

River, and the Merced River, which deliver an average of 66 percent of the San Joaquin River's annual flow (Domagalski and Munday 2003).

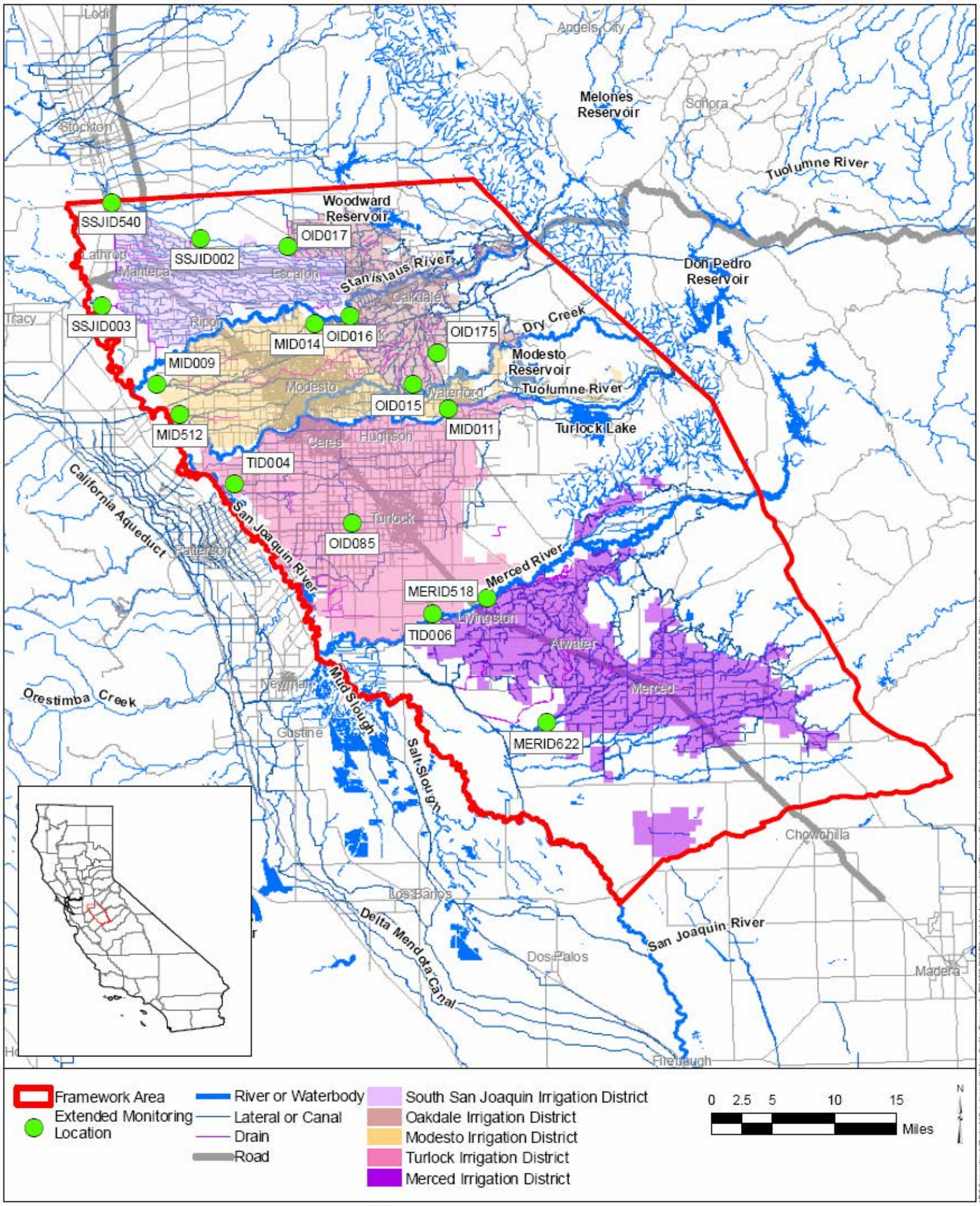


Figure 1. East San Joaquin Water Quality Framework Study Area and Monitoring Locations

Several water quality issues have been identified within the San Joaquin River including, low dissolved oxygen levels and elevated concentrations of salinity, boron, chlorpyrifos, and diazinon. To manage water quality within the river, several Total Maximum Daily Loads (TMDLs) have been developed and are currently being implemented. Several water quality monitoring programs also exist to determine potential sources and calculate loads of constituents of concern going into the river. To help evaluate the contribution of east side tributaries to water quality issues in the San Joaquin River, the five irrigation districts took a proactive approach to monitor water quality within the Framework study area. Funded by a California Proposition 13 Drinking Water Program grant, the five irrigation districts developed a watershed organizational approach to monitor water quality, evaluate best management practices and implementation activities, and provide education and outreach to the urban and agricultural communities. The Framework structure is described in further detail in Hunt et al. 2007, also found in these proceedings.

The water quality monitoring plan was built upon programs already under way by the five irrigation districts, Coalition groups, and the Dissolved Oxygen (DO) TMDL Upstream Monitoring Program. The goals of the monitoring program include identification and evaluation of the following:

- Elevated concentrations of constituents above initial screening thresholds (IST)
- Potential sources, causes, and impacts of elevated concentrations
- The degree of implementation of management measures for improving water quality

STUDY DESIGN AND SAMPLING/ANALYSIS METHODS

Previous water quality monitoring results indicate that during the irrigation season, general water quality constituents, such as pH, Total Dissolved Solids (TDS), low DO, and Electrical Conductivity (EC), periodically exceed water quality objectives. During the storm water season, historic data indicates infrequent detections of various pesticides at concentrations exceeding water quality thresholds (Hunt et al. 2007). These previous data were taken into consideration when developing the Framework monitoring plan to determine station locations, sampling parameters, and timing of sampling.

Water Quality Monitoring Sites

Forty-eight water quality monitoring sites were chosen within the Framework study area. Monitoring sites were chosen to (1) represent discharge potentially affected by a variety of land uses, (2) represent and sample the majority of the outflow leaving each irrigation district, (3) integrate the various monitoring projects currently under way within the Framework study area, and (4) characterize source water inflows into each irrigation district. Sixteen sites were monitored during two storm events in the storm season and twice during the irrigation season (May – September) for an extended list of parameters (Figure 1). All 48 sites were monitored every two weeks during the irrigation season for a set of standard parameters. The current paper will focus on the sixteen sampling sites sampled for the extended set of parameters. The sixteen sampling sites and dates sampled are presented in Table 1.

Table 1. Summary of Monitoring Sites and Sampling Events

Irrigation District	Monitoring site	Station ID	Storm Event 1		Strom Event 2		Irrigation Season	
			Sample 1 18, 19 December 2006	Sample 2 21 December 2006	Sample 1 28 February 2006	Sample 2 2 March 2006	First Event 13 & 14 June 2006	Second Event 9 & 10 August 2006
South San Joaquin	Drain 14 at Lone Tree Creek	SSJID002	Y	Y	No water present	No water present	Y	Y
	Drain 11 at Walsal Slough	SSJID003	Y	Y	Y	Y	Y	Y
	French Camp Open Canal	SSJID540	Not sampled : no flowing water	Not sampled : no flowing water	Y	Y	Y	Y
Oakdale	Coulter Pond	OID015	Y	Y	Y	Y	Y	Y
	Langworth Pipeline	OID016	Not sampled : no flowing water	Not sampled : no flowing water	Not sampled: no water present	Not sampled: no water present	Y	Y
	Sweet Lateral	OID017	Not sampled due to safety issues	Not sampled due to safety issues	Not sampled: no water present	Not sampled: no water present	Y	Y
	Union Drain	OID175	Y	Y	Y	Y	Y	Y
Turlock	Highline Outflow	TID006	Y	Y	Y	Y	Y	Y
	Upper Lateral 4 drop 14	TID085	Not sampled due to safety issues	Not sampled due to safety issues	Y	Y	Y	Y
	Westport Drain	TID508	Y	Y	Y	Y	Y	Y
Merced	Bear Creek at West Boundary	MERID622	Y	Y	Y	Y	Y	Y
	Livingston Canal Outflow to Merced River	MERID518	Y	Y	Y	Y	Y	Y
Modesto	Main Drain Outflow	MID009	Y	Y	Y	Y	Y	Y
	Waterford Lower Main Outflow	MID011	Y	Y	Y	Y	Y	Y
	Spenker Outflow	MID014	Y	Y	Y	Y	Y	Y
	Lateral 4 Outflow	MID512	Y	Y	Y	Y	Y	Y

List of Monitoring Parameters

The standard list of parameters was developed to include many of the parameters currently being analyzed by the five irrigation districts for the Irrigated Lands Conditional Waiver program (administered by the Central Valley Regional Water Quality Control Board (CVRWQCB), constituents of concern under the California Bay Delta Authority Drinking Water Program, as well as some constituents analyzed under the DO TMDL Upstream Monitoring Program. The extended list of parameters included acute water column toxicity, sediment toxicity pesticides, and metals. The extended list was analyzed in conjunction with the standard list of parameters during the sampling events mentioned above. Table 2 presents the standard and extended lists of monitoring parameters analyzed under the Framework monitoring program.

Table 2. Standard and Extended Monitoring Parameters

	Parameters Measured	Method	Reporting Limit	Units
Standard Parameters				
Physical Parameters				
	Dissolved Oxygen	Field		mg/L
	Flow	Field		CFS
	pH	Field		Standard Units
	Temperature	Field		Celsius
	Electrical Conductivity	Field		uS/cm
	Turbidity	Field/EPA 180.1	0.3	NTU
	TSS	EPA 160.2	10	mg/L
	TDS	EPA 160.1	10	mg/L
	Bromide	EPA 300.0	0.5	mg/L
Nutrients and Organic Carbon				
	Total Kjeldahl Nitrogen (TKN)	EPA 351.2	0.5	mg/L
	Nitrate + Nitrite or Nitrate as N	EPA 300.0/353.2	0.12	mg/L
	Phosphorous	EPA 6010B	0.05	mg/L
	Total Organic Carbon (TOC)	EPA 415.1	0.5	mg/L
	Dissolved Organic Carbon (DOC)	EPA 415.1	0.5	mg/L
Extended Parameters				
Organophosphate Pesticides				
	Azinphos-Methyl [Guthion]	EPA 8141A	1	µg/L
	Bolstar	EPA 8141A	0.1	µg/L
	Chlorpyrifos	EPA 8141A	0.5	µg/L
	Diazinon	EPA 8141A	0.5	µg/L
	Dimethoate	EPA 8141A	0.1	µg/L
	Ethoprop	EPA 8141A	0.1	µg/L
	Methyl Parathion	EPA 8141A	0.1	µg/L
	Mevinphos	EPA 8141A	0.7	µg/L
	Naled	EPA 8141A	0.5	µg/L

Table 2. Standard and Extended Monitoring Parameters (continued)

	Parameters Measured	Method	Reporting Limit	Units
	Phorate	EPA 8141A	0.1	µg/L
	Tokuthion	EPA 8141A	0.1	µg/L
Pyrethoid Insecticides				
	Cypermethrin	EPA 8081A	0.05	µg/L
	Esfenvalerate/Fenvalerate	EPA 8081A	0.02	µg/L
	Lambda Cyhalothrin	EPA 8081A	0.02	µg/L
	Permethrin	EPA 8081A	0.02	µg/L
Herbicides				
	Diuron	EPA 8321A	1	µg/L
	Glyphosate	EPA 547	10	µg/L
	Merphos Oxide	EPA 8141A	0.1	µg/L
	Pendimethalin	EPA 8141A	0.1	µg/L
	Trichlopyr	EPA 8151	5	µg/L
	Trifluralin	EPA 8141A	0.1	µg/L
Volatile Organics				
	Cis & Trans 1,3- Dichloropropene	EPA 8260B	0.5	µg/L
Inorganics				
	Copper	EPA 6010B	5	mg/L
	Selenium	FGS-055	0.02	µg/L
	Zinc	EPA 6010B	50	mg/L
	Potassium	EPA 6010B	1	mg/L
	Phosphate as P	EPA 300.0	50	mg/L
Toxicity				
	Ceriodaphnia dubia (acute toxicity)	a		
	Pimephales promelas (acute toxicity)	a		
	Selenastrum capriconutum (96 hour)	b		
	Hyallela azteca	c		
	Phase I Toxicity Identification Evaluation (TIE)	d		

*Frontier GeoSciences Method

[a] Methods for measuring the acute toxicity of effluents and receiving waters to freshwater and marine organisms. USEPA Office of Water. EPA-821-R-02-012.

[b] Short Term Methods for estimating the chronic toxicity of effluents and receiving waters to freshwater organisms. USEPA Office of Water. EPA-821-R-02-013.

[c] Methods for measuring the toxicity and bioaccumulation of sediment-associated contaminants with freshwater organisms. USEPA Office of Research and Development. EPA-600-R-99-064.

[d] Methods for Aquatic Toxicity Identification Evaluations. Phase I Toxicity Characterization Procedures. Office of Research and Development, Duluth, MN. EPA-600-3-88-034.

RESULTS AND DISCUSSION

Table 3 presents a summary of the extended water quality parameter results for the Framework study. Fifteen of the thirty parameters analyzed were detected above analytical reporting limits at least once during the four sampling events. Parameters that were detected above the analytical reporting limits, were compared to initial screening thresholds (IST) comprised of regulatory and non-regulatory water quality objectives including TMDLs, state and federal drinking water standards, Central Valley Regional Water Quality Control Board Basin plan, US Environmental Protection Agency (USEPA) aquatic life ambient water quality criteria, etc. Those parameters that were detected at concentrations above the IST are presented graphically and discussed further below. An in depth analysis on the correlation of land use and parameters detected in the Framework area during the study program are presented in Cooke et al. 2007, also found in these proceedings.

Organophosphate Pesticides

Three of the four detected organophosphate pesticides (methyl parathion, chlorpyrifos, and diazinon) were detected above ISTs during the sampling period (Table 3). Methyl parathion was detected once during the first storm event in December 2005 at 0.18 µg/L, which was greater than the interim instantaneous maximum ambient water quality criteria of 0.08 µg/L recommended by California Department of Fish and Game for the protection of aquatic life. Methyl parathion was not detected at any other time during the sampling program.

Chlorpyrifos was detected in five of the 82 samples, once during the second storm event in March 2006 and four times during the irrigation season (Figure 2). Detected concentrations ranged from 0.011 to 0.041 µg/L and occurred in five different locations spread throughout the Framework study area, MID011, OID175, SSJID003, SSJID540, and TID006, indicating no persistent spatial trend. The IST is 0.015 µg/L, which is the chronic TMDL criterion for the lower San Joaquin River. Two of the detected concentrations were above the IST, 0.025 µg/L at OID175 during the second storm event in March 2006 and 0.041 µg/L at SSJID540 during the first irrigation season event in June 2006.

Table 3. Summary Statistics of the ESJWQF Monitoring Program Extended Sampling Events

	Fraction	Analyte	Unit	No. of Samples	Detection Rate	Mean	Std Dev	Min Detected	Max Detected	Initial Screen Threshold (IST)	No. of Samples Exceed IST	% of Samples Exceed IST
Organophosphate Pesticides												
	Total	Azinphos methyl	µg/L	82	0%	-	-	-	-	0.01	0	0%
	Total	Bolstar	µg/L	82	0%	-	-	-	-	-	-	-
	Total	Chlorpyrifos	µg/L	82	6%	0.0207	0.0072	0.011	0.041	0.015	2	2%
	Total	Diazinon	µg/L	82	17%	0.0478	0.0858	0.03	0.5	0.1	8	10%
	Total	Dimethoate	µg/L	82	7%	0.0680	0.0836	0.13	0.69	1.4	0	0%
	Total	Ethoprop	µg/L	82	0%	-	-	-	-	-	-	-
	Total	Parathion, Methyl	µg/L	82	1%	0.0516	0.0144	0.18	0.18	0.08	1	1%
	Total	Mevinphos	µg/L	82	0%	-	-	-	-	-	-	-
	Total	Naled	µg/L	82	0%	-	-	-	-	14	0	0%
	Total	Phorate	µg/L	82	0%	-	-	-	-	-	-	-
	Total	Tokuthion	µg/L	82	0%	-	-	-	-	-	-	-
Pyrethroid Insecticides												
	Total	Cypermethrin, total	µg/L	69	1%	0.0252	0.0016	0.052	0.052	0.002	1	1%
	Total	Esfenvalerate/Fenvalerate, total	µg/L	69	1%	0.0100	0.0001	0.011	0.011	-	-	-
	Total	Cyhalothrin, lambda, total	µg/L	69	1%	0.0100	0.0001	0.011	0.011	35	0	0%
	Total	Permethrin, total	µg/L	69	0%	-	-	-	-	0.03	0	0%
Herbicides												
	Total	Diuron	µg/L	69	22%	2.28	10.72	0.4	89	10	2	3%
	Total	Glyphosate	µg/L	55	7%	6.86	10.98	5	56	700	0	0%
	Total	Def	µg/L	82	0%	-	-	-	-	0.2	0	0%
	Total	Prowl	µg/L	82	10%	0.0776	0.1264	0.058	0.85	280	0	0%
	Total	Triclopyr	µg/L	56	9%	0.765	1.705	0.059	11	300	0	0%
	Total	Trifluralin	µg/L	82	5%	0.0595	0.0658	0.068	0.64	17	0	0%
Volatile Organics												
	Total	Dichloropropene, cis 1,3-	µg/L	55	0%	-	-	-	-	0.5	0	0%
	Total	Dichloropropene, trans 1,3-	µg/L	55	0%	-	-	-	-	0.5	0	0%
Inorganics												
	Total	Copper	mg/L	82	37%	0.00964	0.03016	0.0051	0.262	*	19	23%
	Dissolved	Copper	mg/L	42	5%	0.00276	0.00131	0.0053	0.0106	*	0	0%
	Total	Zinc	mg/L	82	7%	0.0352	0.0538	0.0571	0.463	*	5	6%
	Dissolved	Zinc	mg/L	42	0%	-	-	-	-	*	0	0%
* Calculated based on Hardness												

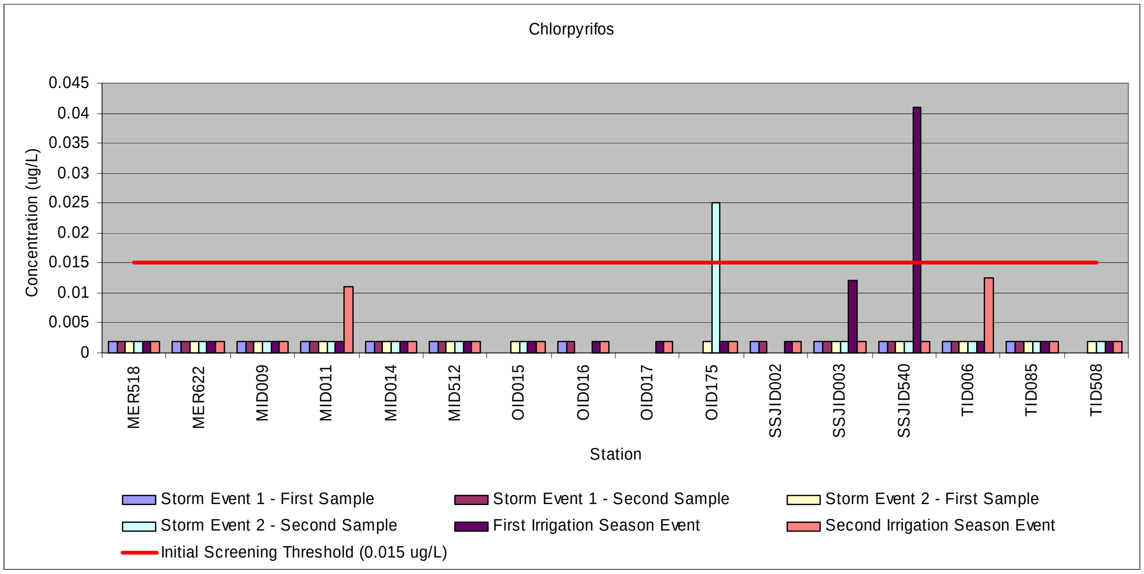


Figure 2. Chlorpyrifos Concentrations Detected During the Sampling Period

The amount of chlorpyrifos use reported within the Framework study area for agricultural uses varies by month, with May and July applications consistently being the highest. Over the last five years the agricultural application rate has not decreased. Overall, the crops most heavily sprayed with chlorpyrifos in the Framework study area are almonds and walnuts during the irrigation season. The timing of the application is reflected in current water quality data with the majority of the detected concentrations measured during the irrigation season.

Diazinon is a dormant season pesticide used most heavily in December, January, and February (DPR 2000-2004). Diazinon is also a constituent of concern in the lower San Joaquin River. The TMDL water quality target of 0.10 µg/L is based on protection of aquatic life from chronic exposure and was used as the IST. All of the detected concentrations during the Framework sampling program were measured during the storm season events, which reflect the timing of the pesticide application.

Diazinon was detected in 14 of the 82 samples collected at concentrations ranging from 0.03 to 0.5 µg/L. Eight of these concentrations were above the IST (Figure 3). During each storm event, two samples were taken at each site. The first sample was taken at the beginning of the storm and the second 72 hours later. During the first storm event in December 2005, diazinon concentrations were detected above the IST at OID016 (0.19 µg/L) and TID085 (0.12 µg/L) in the first sample taken. Three days later a second sample was taken. Diazinon concentrations were still detected at the same two stations above the IST, 0.2 µg/L and 0.33 µg/L at OID016 and TID085 respectively, indicating persistent elevated concentrations throughout the storm event at these sites. The second sample also revealed a diazinon concentration above the IST (0.5 µg/L) at SSJID002. During the second storm event in late February 2006/ early March 2006, persistent diazinon concentrations were measured at MID512 above the IST at concentrations of 0.27 µg/L and 0.4 µg/l, in the first and second samples respectively. Also, at SSJID540, diazinon was measured above the IST at 0.21 µg/L in the first sample at the beginning of the storm, but was not detected two days later in the second sample.

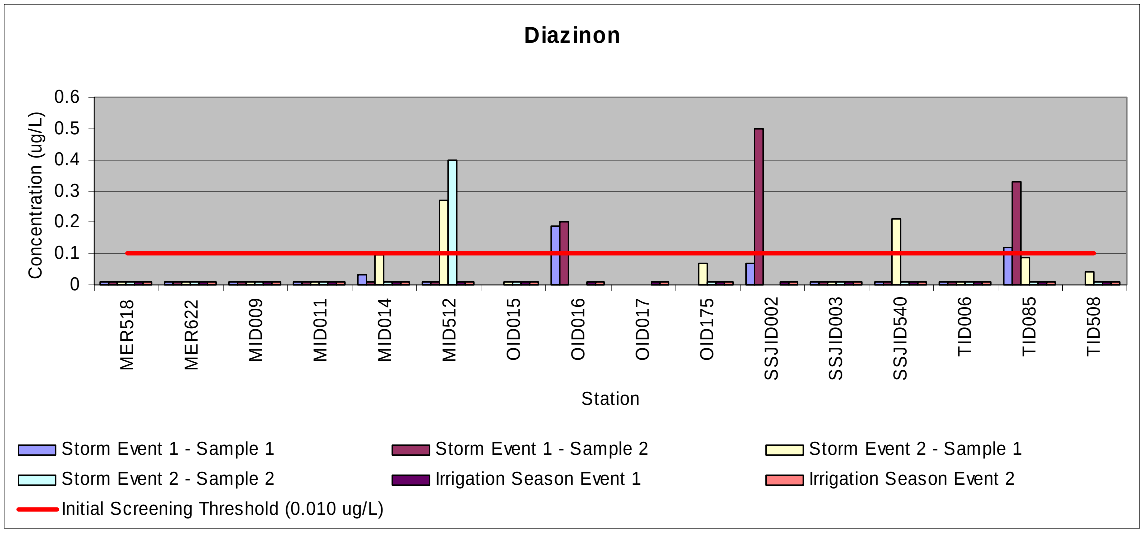


Figure 3. Diazinon Concentrations Detected During the Sampling Period

Pyrethroid Insecticides

Four pyrethroid insecticides (cypermethrin, esfenvalerate, fenvalerate, and lambda cyhalothrin) were included in the Framework sampling program extended analysis (Table 2) due to recent studies indicating that pyrethroid pesticides may lead to toxicity in water bodies of the Central Valley. Three of the four insecticides (cypermethrin, esfenvalerate and lambda cyhalothrin) were detected during the study. Cypermethrin was detected during the first irrigation season event at OID016 at a concentration of 0.039 µg/L, which was above the IST of 0.002 µg/L which is the interim one-hour average concentration recommended by California Department of Fish and Game for the protection of aquatic life. Esfenvalerate and lambda cyhalothrin were also detected in the same sample both at concentrations of 0.0105 µg/L. No IST was identified for esfenvalerate; however, the lambda cyholothrin concentration was well below the IST of 35 µg/L, which is based on USEPA mammalian toxicity data from the Integrated Risk Information System database.

Herbicides

Several herbicides were detected during the four sampling events including glyphosate, pendimethalin, triclopyr, trifluralin, and diuron. Glyphosate was detected in 4 out of the 55 samples collected, ranging in concentration between 5 and 56 µg/L. All concentrations were well below the IST of 700 µg/L, which was based on both the USEPA Integrated Risk Information System database and the USEPA Drinking Water Health Advisory. Pendimethalin was only detected during the storm season in 8 out of 55 samples with concentrations ranging from 0.058 to 0.85 µg/L. None of the pendimethalin concentrations were above the IST of 280 µg/L, however, it is interesting to note that it was consistently detected at station TID085 in all four samples during the storm sampling events. Station TID085 receives urban runoff from the City of Turlock during the winter, when the canals are not used for irrigation supply water. Tricloypr was detected in 5 out of 56 samples or 9% of the samples collected (Table 3). Concentrations ranged from 0.059 to 11 µg/L well below the IST of 300 µg/L, which is a LC50 level (i.e., the lethal concentration at which 50 percent of a test population is killed). Trifluralin was detected in 5 of 82 samples with concentrations ranging from 0.068 to 0.64 µg/L which was also below the IST of 17 µg/L. The majority of the tricloypr and trifluralin detections were also measured during the storm season.

Diuron was the only herbicide that was detected above an IST of 10 µg/L, based on the USEPA Drinking Water Health Advisories or Suggested No-Adverse Response Levels (SNARLs) for toxicity other than cancer risk. Although there was a 22% detection rate during the sampling program, only two of 69 samples were above the IST (Figure 4). These two concentrations, 89 µg/L and 12 µg/L, were measured in samples collected during the storm season at SSJID002 (first storm event) and MER622 (second storm event).

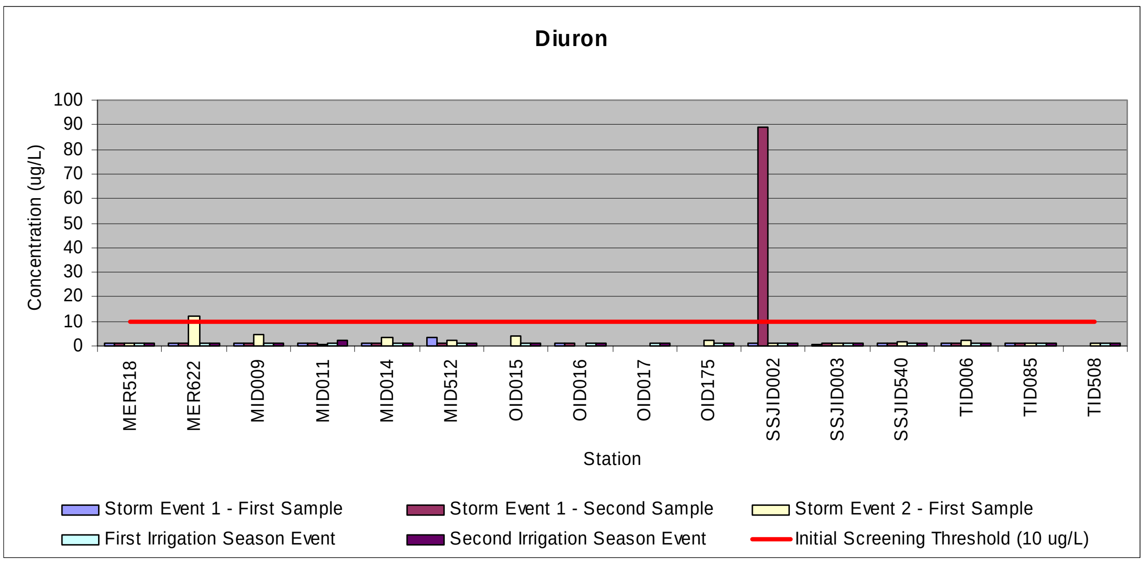


Figure 4. Diuron Concentrations Detected During the Sampling Period

Metals

Total and dissolved copper and zinc were analyzed as part of the extended parameter list. Screening criteria are dependent on a formula based hardness and were calculated for each sample based on EPA 40 CFR Part 131 and presented in Tables 4 and 5. Neither dissolved copper or dissolved zinc concentrations exceeded calculated chronic copper criteria throughout the sampling period.

Total copper was detected in 37% of the 82 samples collected (Table 3) and ranged from 0.0038 to 0.262 mg/L. Nineteen of those detections were greater than the calculated IST, which was the chronic water quality criteria based on hardness (Table 4). Twelve of those detected concentrations were measured during the storm season at stations OID175, OID016, TID085, MER518, MID011, MID512, and MID014, the highest of which was detected in a sample from OID175 at 0.0749 mg/l during the second storm event. Seven elevated concentrations were measured during the irrigation season at OID175, TID006, MID009, SSJID002, MER518, OID015, and TID085, the highest of which was detected in a sample from MID009at 0.262 mg/l during the first irrigation season event. However, this sample is suspect as the copper concentration measured was similar to the laboratory spike concentration of 0.260 mg/L, but the sample was disposed of before the laboratory could verify that it was indeed a spiked sample. None of the dissolved copper concentrations measured were above the calculated IST.

Table 4. Total Copper Concentrations Above Calculated ISTs
(Chronic Water Quality Criteria)

Station ID	Sample Date	Copper Concentration [mg/L]	Hardness [mg/L]	Chronic Copper Criteria Based on Hardness [mg/L]
OID016	12/18/2005	0.0145	66.7	0.0066
TID085	12/18/2005	0.0087	51	0.0052
MER518	12/21/2005	0.0052	19.2	0.0023
MID014	12/18/2005	0.0085	75.6	0.0073
OID175	2/28/2006	0.0479	413	0.0313
OID175	3/2/2006	0.0749	166	0.0144
MER518	3/2/2006	0.0174	55.2	0.0056
MID011	2/28/2006	0.0117	30.3	0.0034
MID011	3/2/2006	0.0137	38	0.0041
MID014	2/28/2006	0.0079	44.5	0.0047
MID014	3/2/2006	0.0073	56	0.0057
MID512	3/2/2006	0.0075	36.8	0.0040
OID175	6/13/2006	0.0052	37.1	0.0040
SSJID002	6/14/2006	0.0218	174	0.0150
TID006	6/13/2006	0.0075	23.4	0.0027
MID009	6/14/2006	0.262	114	0.0104
MER518	8/9/2006	0.0052	25	0.0029
OID015	8/9/2006	0.0076	54.4	0.0055
TID085	8/10/2006	0.0441	66.5	0.0066

Notes
Chronic Hardness Criteria calculated using = $e^{\{0.8545[\ln(\text{hardness})]-1.702\}}$
Equations from A Compilation of Water Quality Goals. Marshack 2003.

Five out of 82 samples had total zinc concentrations above the calculated IST, which was the chronic water quality criteria based on hardness (Table 5). Four of the samples were from the storm season from SSJID540, TID085, OID175 and MID011 and ranged in concentrations from 0.0581 to 0.463 mg/L. The remaining sample detected above the calculated IST was measured during the irrigation season at TID085 at a concentration of 0.225 mg/L. As with dissolved copper, none of the dissolved zinc concentrations were measured above the calculated IST.

Table 5. Total Zinc Concentrations Above Calculated ISTs
(Chronic Water Quality Criteria)

Station ID	Sample Date	Zinc Concentration [mg/L]	Hardness Concentration [mg/L]	Zinc Criteria Based on Hardness [mg/L]
SSJID540	12/19/2005	0.0581	30.3	0.044
TID085	12/18/2005	0.0791	51	0.068
MID011	12/19/2005	0.103	73.3	0.092
OID175	3/2/2006	0.463	166	0.184
TID085	8/10/2006	0.225	66.5	0.085

Notes

Hardness Criteria calculated using = $e^{\{0.8473[\ln(hardness)]+0.884\}}$

Equation from A Compilation of Water Quality Goals. Marshack 2003.

SUMMARY

During the Framework water quality monitoring program, several parameters were detected within the Framework area. The OP pesticide chlorpyrifos was detected primarily during the irrigation season, which is consistent with pesticide use trends as the highest use of the pesticide occurs during the summer months. Diazinon was also detected during the study, but was exclusively detected during the storm season. This is also consistent with pesticide use trends in the region, as diazinon is primarily used as a dormant spray during the winter. These data indicate that despite recent new regulatory requirements to phase out the use of both of these pesticides, they are still being transported to surface water to some extent.

Pyrethroid pesticides have been used to a greater extent in recent years due to the increased restrictions on the use of the OP pesticides. Cypermethrin, esfenvalerate, and lambda cyhalothrin were each detected during the study, but each were only detected once indicating no spatial or temporal trends.

The metals copper and zinc were the most frequently detected parameters measured during the four sampling events. The majority of detections for both metals occurred during the storm season, however, both were still detected during the irrigation season. Sources of copper and zinc in the environment may be linked to tires and brake linings from motor vehicles.

REFERENCES

Domagalski, J.L., and C. Munday. 2003. *Evaluation of Diazinon and Chlorpyrifos Concentrations and Loads, and Other Pesticide Concentrations, at Selected Sites in the San Joaquin Valley, California, April to August, 2001.* Water-Resources Investigations Report 03-4088. U.S. Department of the Interior, U.S. Geological Survey, Sacramento, CA. Prepared in cooperation with the California Department of Pesticide Regulation.

Marshack, Jon. 2003. *A Compilation of Water Quality Goals. August 2003 Edition.* Prepared for the Central Valley Regional Water Quality Control Board.

EAST SAN JOAQUIN WATER QUALITY FRAMEWORK: EFFECTS OF URBANIZATION ON WATER QUALITY

T. Cooke[1]
L.S. Hunt[2]
J. Edmunds[3]
W. Ward[4]

ABSTRACT

Historical and recent surface water quality data measured in the East San Joaquin Water Quality Framework region indicate that a number of parameters, including pesticides, nutrients, and inorganics, have been detected, sometimes at concentrations that exceed regulatory water quality objectives or other nonregulatory screening thresholds. Because much of the land use in the region is agricultural, it is often assumed that agriculture is the primary source of water quality pollutants. Although the contributions of nonagricultural sources such as urban, residential, and industrial sources have not been well quantified, in some cases they may account for a significant portion of the pollutant load. For examples, two of the inorganics most frequently found at elevated concentrations are copper and zinc, which may occur in urban and highway runoff due to brake pad and tire wear. In addition, many of the pesticides detected in surface water in the region are used for both nonagricultural and agricultural purposes. In some cases, residential use is estimated to account for up to half the use of certain pesticides. One of the objectives of the work conducted under the Framework is to provide information to help differentiate between urban and agricultural sources, using data on pesticide use, land use, and spatial and temporal trends in water quality data. This knowledge will be useful in formulating management practices to help reduce pollutant loads to surface water bodies in the region.

LOCATION AND BACKGROUND

The East San Joaquin Water Quality Framework provides a cost-effective watershed organizational structure for cooperative and coordinated water quality improvement activities. This structure helps to facilitate decisions on how to attain water quality objectives for the San Joaquin River eastside tributaries, and manage loads entering the San Joaquin River to protect water quality in the Bay-Delta. The Framework study area is located in the San Joaquin Valley on the east side of the San Joaquin River. The major tributaries that transect the area are the Merced, Tuolumne, and Stanislaus rivers, the combination of which delivers an average of 66 percent of the San Joaquin River's annual flow (Domagalski and Munday 2003). The study area

[1] Manager – Water Environment Department; URS Corporation, 1333 Broadway, Oakland CA 94612; terry_cooke@urscorp.com.

[2] Senior Environmental Engineer; URS Corporation, 1333 Broadway, Oakland CA 94612; lisa_hunt@urscorp.com.

[3] Senior Environmental Scientist; URS Corporation, 1333 Broadway, Oakland CA 94612; jody_edmunds@urscorp.com.

[4] Assistant General Manager – Water Operations; Modesto Irrigation District, P.O. Box 4060, Modesto, CA 95352; walterw@mid.org.

encompasses approximately 600,000 acres, including areas served by five irrigation districts: Turlock, Modesto, South San Joaquin, Merced, and Oakdale (see Figure 1). A companion paper provides more information on the characteristics of the Framework study area and approach (Hunt, L.S. et. al., 2007).

The climate of the San Joaquin Valley is Mediterranean with hot, dry summers and mild, rainy winters. The total annual precipitation is approximately 12 inches, with most precipitation occurring between November and March. The summer high mean temperature is about 91 degrees Fahrenheit, and the winter mean temperature is about 40 degrees Fahrenheit. Land use is dominated by agriculture, which is dependent upon the water districts for distribution of water during the annual irrigation season. The normal irrigation season extends from March to late October or early November. Peak irrigation water use occurs in July. In addition to various agricultural land uses, some urban and suburban developments within the study area have experienced growth in recent years.

WATER QUALITY ISSUES IN RECEIVING WATERS

Multiple water quality issues are currently being addressed in the San Joaquin River and its tributaries under various programs. Principal parameters of concern include salinity and boron, nutrients and algal blooms leading to low dissolved oxygen, pesticides (chlorpyrifos and diazinon), selenium, mercury, and bacteria. Table 1 shows the Total Maximum Daily Load programs and their priority for the San Joaquin River. In addition, low river flow and water levels are a concern for fisheries management agencies and downstream agricultural water users.

Table 1. Total Maximum Daily Load Priority List for Potentially Affected Waters

Parameter	San Joaquin River	Sacramento/San Joaquin Delta
Boron	H	–
Chlordane	–	L
Chlorpyrifos	H	–
Copper	–	M
DDT	L	L
Diazinon	H	M
Dieldrin	–	L
Dioxin compounds	–	M
Dissolved oxygen	H	–
Electrical conductivity	H	H
Exotic species	–	H
Furan compounds	–	H
Group A Pesticides	L	–
Mercury	L	H
Nickel	–	L
PCBs	–	M
PCBs (dioxin-like)	–	H
Pesticides	–	–
Selenium	H	L
Unknown toxicity	–	M

DDT=dichlorodiphenyltrichloroethane, H=high-priority constituent, L=low-priority constituent, M=medium-priority constituent, PCBs=polychlorinated biphenyls

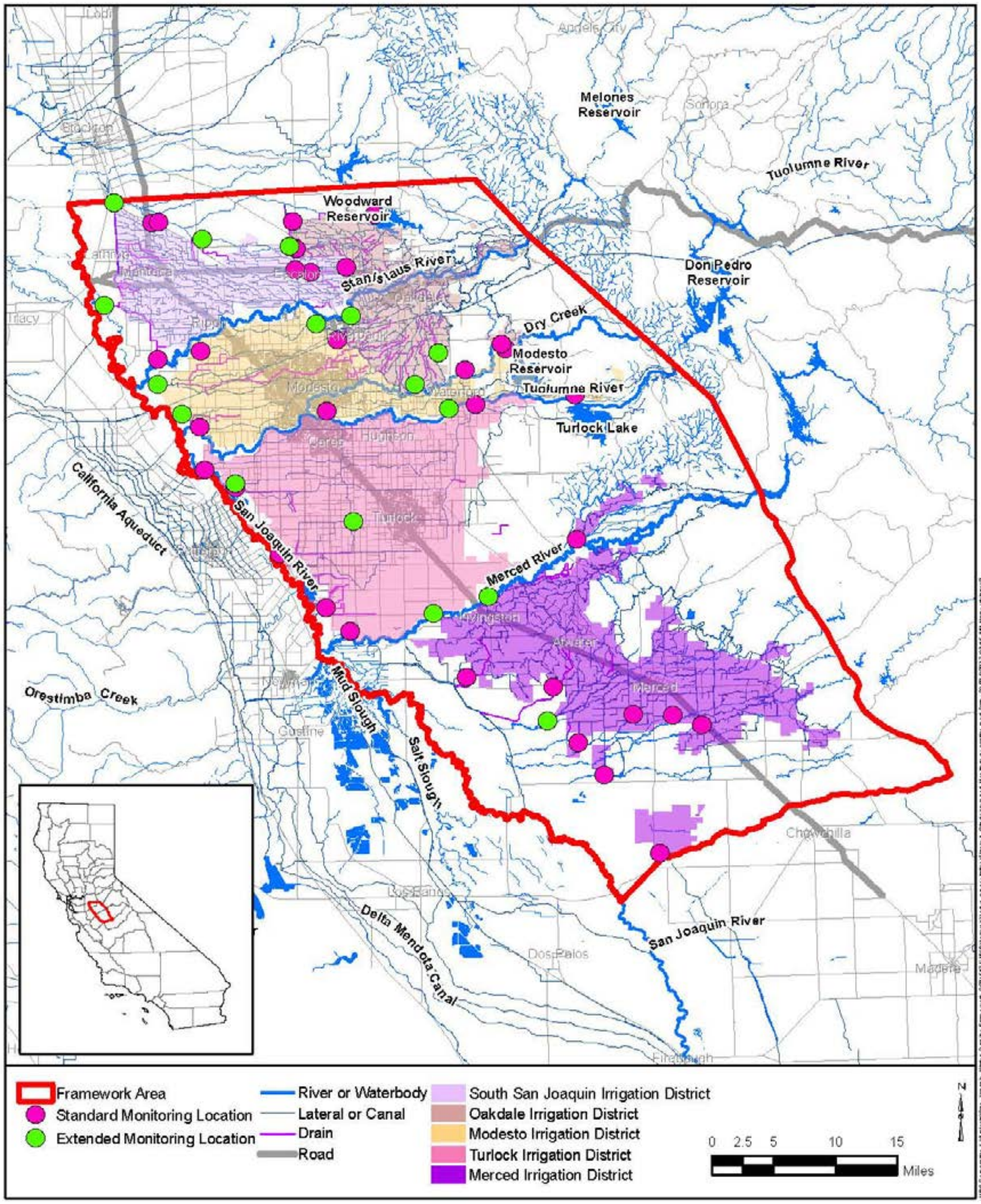
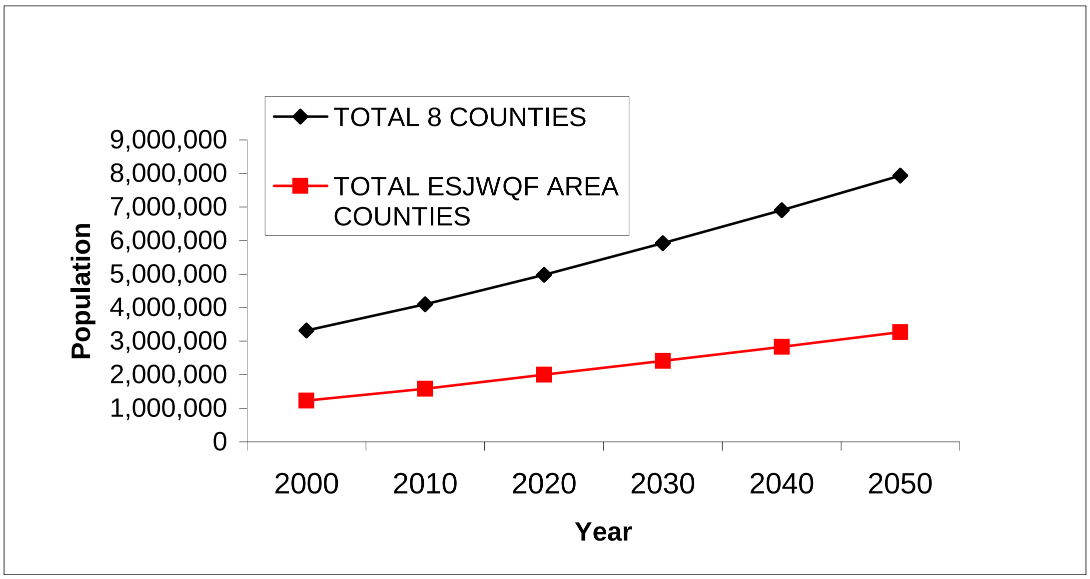


Figure 1. Framework Study Area and Monitoring Locations

The San Joaquin Valley has experienced and is expected to continue to experience rapid population growth (Table 2). Figure 2 shows the projected population of the eight counties that comprise the entire San Joaquin Valley and the three major counties (Merced, Stanislaus, and San Joaquin) encompassed by the Framework Area for 2000 to 2050.

Table 2. Population Growth in the San Joaquin Valley and Framework Area

	Year					
County	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Fresno	803,401	949,961	1,114,654	1,297,476	1,476,699	1,658,281
Kern	664,694	808,808	950,112	1,114,878	1,325,648	1,549,594
Kings	129,823	156,334	184,751	223,767	252,762	282,364
Madera	124,372	150,278	183,966	219,832	259,353	302,859
Merced	210,876	277,715	360,831	437,880	528,788	625,313
San Joaquin	567,798	747,149	989,462	1,229,757	1,457,128	1,707,599
Stanislaus	449,777	559,051	653,841	744,599	843,523	941,562
Tulare	369,355	447,315	543,749	650,466	754,790	867,482
Total Eight Counties	3,320,096	4,096,611	4,981,366	5,918,655	6,898,691	7,935,054
Total Framework Area Counties	1,228,451	1,583,915	2,004,134	2,412,236	2,829,439	3,274,474



Data Source: State of California Department of Finance, Demographic Research Unit (May 2004)
Graph Source: The Great Valley Center (www.greatvalley.org, Modesto, California)

Figure 2. Projected Population Growth in the San Joaquin Valley and Framework Area

As the population expands, land use is converted from primarily agricultural to urban. The purpose of this paper is to explore the potential implications of such changes on surface water quality as it flows through the irrigation system and into receiving waters.

DISTRICT CONVEYANCE SYSTEMS

Initially, the five irrigation districts in the Framework area were formed to supply and convey surface water from the upper watershed storage reservoirs to growers during the summer irrigation season. As population increased many cities and towns experienced increased local flooding in the winter due, in part, to the increase in impervious surfaces and the relatively flat terrain. To help alleviate these flooding problems many irrigation districts have allowed cities to use the irrigation district canals in the winter to convey floodwaters out of the city to nearby creeks and waterways. During the summer irrigation season some urban areas also use the irrigation system canals to convey dry weather flows (such as landscape irrigation runoff, washwater, construction dewatering, and other nuisance waters) out of the urban areas.

In addition to the primary use of canals as a distribution system for high quality reservoir releases to growers, irrigation system canals also accept tailwater return flows from local growers, pumped groundwater from district-operated supply wells, and groundwater from level control drainage wells. In some irrigation districts the open canals must be operated at sufficient heads to fill supply turnouts to ensure water is supplied to downstream users. This scenario often requires release of carriage water from the supply reservoirs to ensure water orders can be delivered. Additionally, some districts are located between other upstream districts and downstream receiving waters and provide conveyance (and use) of neighboring district releases through their system into receiving waters. An example of Modesto Irrigation District is shown on Figure 3. The figure shows the irrigation system canals, drainage ditches, and land use (including developed, urban areas). Also shown are the points of discharge from Oakdale Irrigation District into the Modesto Irrigation District system. Framework monitoring stations and their potential drainage area of influence for the winter and summer seasons are also displayed.

As a result of this mixed-use conveyance system, many potential water sources may contribute water to the canal system and the relative proportion of each varies from location to location and over time. Such mixed use conveyance makes it difficult to distinguish specific water quality issues associated with different sources unless sources are sampled prior to discharge into the system.

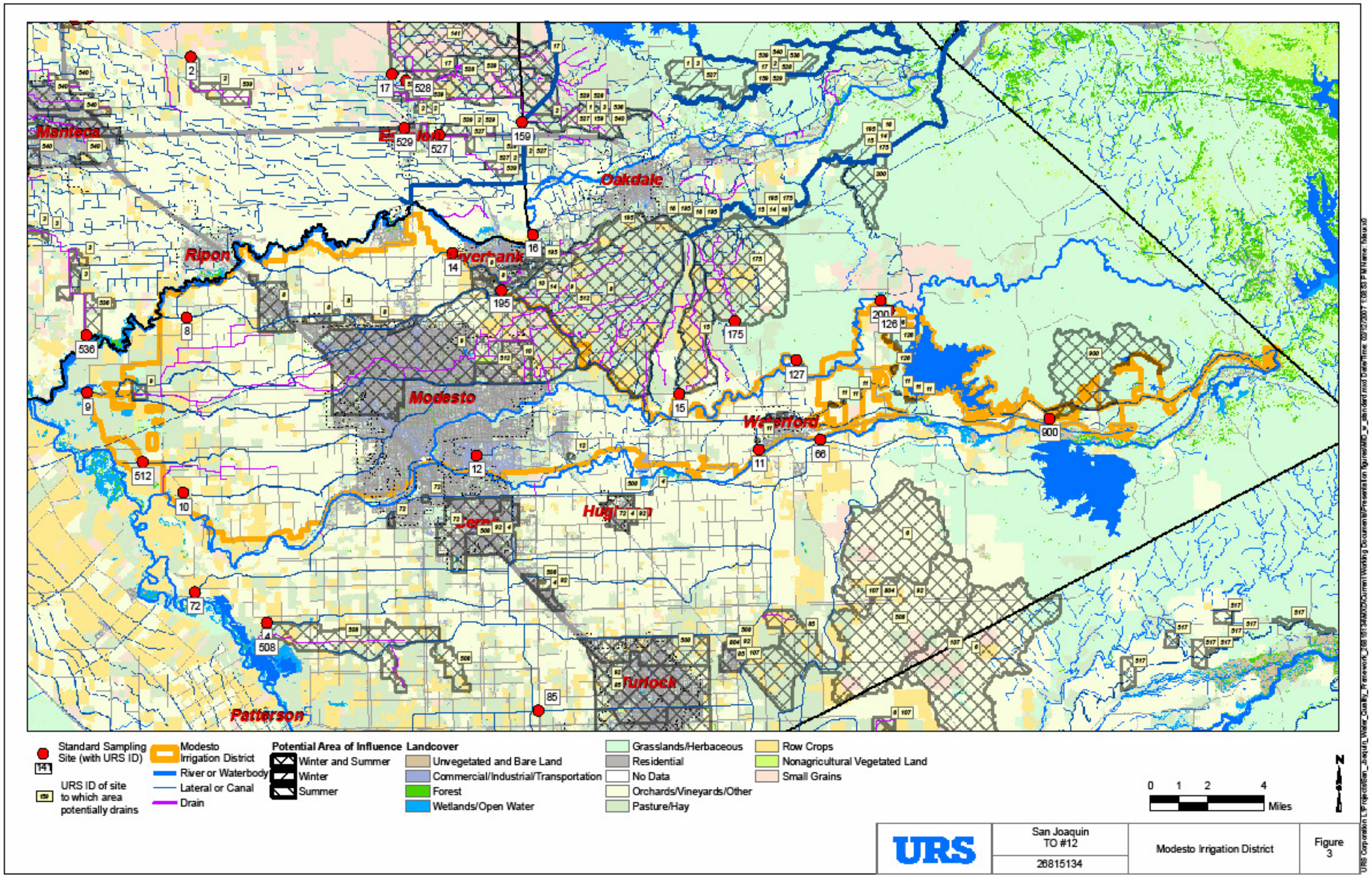


Figure 3. Sampling Locations and Landuse in the Vicinity of Modesto Irrigation District

FRAMEWORK MONITORING PROGRAM

Specifics of the Framework monitoring program are provided in companion papers (Hunt et al. 2007; Edmunds et al. 2007). Briefly, 48 water quality monitoring sites were chosen within the Framework study area as shown on Figure 1. Monitoring began in December 2005 and continued through the 2006 irrigation season. Two storm events were targeted during the nonirrigation season, and storm samples were collected at a subset of 16 sites that capture the most stormwater runoff and are accessible during a storm. Discrete samples were taken during the storm event and then also 2 days after the storm event, as required by the Discharges from Irrigated Lands Program (Ag Waiver) administered by the Central Valley Regional Water Quality Control Board. Monitoring was conducted twice a month during the irrigation season.

The standard list of parameters includes water sampling for flow, pH, dissolved oxygen, electrical conductivity, total dissolved solids (TDS), total suspended solids (TSS), organic carbon, and nutrients. The extended parameter list includes water sampling for metals, pesticides, and water column toxicity as well as sediment quality and toxicity analysis.

URBAN RUNOFF DATA SOURCES

Because the emphasis of the Framework was on characterization of district operational outflows from the irrigation system, water quality data from other urban runoff control programs were used to supplement the Framework data for analysis of potential urbanization effects. The City of Modesto conducts a Stormwater Management Program. In accordance with the requirements of the Clean Water Act for Municipal Separate Storm Sewer Systems (MS4s) the City has obtained a National Pollutant Discharge Elimination System (NPDES) permit (CAS083526 and Board Order No. R5-2002-0182) and conducts monitoring at two sites within the urban storm drainage system and at the inlet and outflow of two detention basins receiving urban runoff. Monitoring has been conducted for two storm events at each of these six stations during Water Year (WY) 2004 and 2005.

Four urban runoff programs in the San Francisco Bay Area conducted water quality monitoring from 1990–1995 as a part of the storm system characterization required under their phase one NPDES MS4 permits. The Bay Area Stormwater Management Agencies Association (BASMAA) conducted a monitoring project that compiled and analyzed data from Alameda Countywide Clean Water Program, Santa Clara Valley Urban Runoff Pollution Prevention Program, Contra Costa Clean Water Program, and Fairfield-Suisun Urban Runoff Management Program (BASMAA 1996). This database includes data from over 500 flow-weighted composite samples collected at stations located throughout the San Francisco Bay Area and provides a baseline for comparison of the Framework and Modesto MS4 data. For this analysis, data from storm drain systems located in the developed areas (including residential, industrial, and commercial land uses) was used to represent urban runoff. These data were mainly collected during WY 1989-1991 with some stations having data through WY 1995.

FRAMEWORK WATER QUALITY DATA ANALYSIS

Framework water quality data were compared to initial screening objectives (ISTs) and examined to determine which parameters were consistently detected and, therefore, amenable to detailed statistical comparisons. Summary detection frequencies, statistics, and results of the IST comparison are presented in Tables 3a (Irrigation Season) and 3b (Wet Season). Data quality assurance, management, validation, and handling of non-detected values are described in Edmunds, et al., 2007. For the statistical analysis, one half the reporting limit value was substituted for non-detected results.

Standard parameters were consistently detected and often showed widely varying concentrations from event to event. For example, nutrient concentrations (phosphorous and nitrate+nitrite) during the irrigation and storm season had a coefficient of variability (CV = Standard deviation/mean) often greater than 180 percent, suggesting widely varying sources or land-use practices in the Framework area. Extended parameters (mostly toxics) were less consistently detected with the exception of hardness, which is a general water quality characteristic, rather than a toxic compound.

Table 3a. Irrigation Season Water Quality Monitoring Results (Detected Compounds Only) Water Year 2006

Analyte	Unit	No. of Samples	Detection Rate	Mean	Std Dev	Median	CV	Min	Max	Initial Screen Threshold (IST)	No. of Samples Exceed IST	% of Samples Exceed IST
Temperature	°C	496	100%	21.9	2.8	21.7	13	13.79	33.99	-	-	-
Oxygen, Dissolved	mg/L	495	100%	9.83	2.76	9.87	28	0.25	20.43	<8	102	21%
TSS	mg/L	480	48%	21.9	38.4	5	175	2	480	-	-	-
Turbidity (Field)	NTU	496	100%	21.8	32.7	11.1	150	1.29	394.1	50	52	10%
TDS	mg/L	480	95%	108	102	77.5	94	10	791	450	7	1%
Specific Conductivity	uS/cm	496	100%	166	186	97.5	112	25	1344	315	75	15%
Hardness as CaCO3	mg/L	32	100%	54.3	53.3	34.8	98	5.3	230	-	-	-
pH	SU	496	100%	7.58	0.61	7.51	8	6.03	9.83	6.5 - 8.5	53	11%
DOC	mg/L	480	94%	4.44	3.99	3.2	90	0.73	47.9	3	254	53%
TOC	mg/L	480	97%	4.45	4.36	3.2	98	1.1	49.6	3	251	52%
TKN	mg/L	480	74%	1.00	1.15	0.75	115	0.27	15.6	-	-	-
NO_3 + NO_2 as N	mg/L	488	75%	1.48	2.94	0.28	199	0.03	22.6	10	13	3%
Diss. Phosphate as P	mg/L	24	13%	0.19	0.31	0.1	167	0.31	1.6	-	-	-
Phosphorus as P	mg/L	479	75%	0.34	0.62	0.12	182	0.05	8.8	0.025	359	75%
Bromide	mg/L	480	3%	0.259	0.063	0.25	24	0.38	1.1	0.05	13	3%
Potassium	mg/L	488	75%	3.30	4.97	1.71	151	1	66.3	-	-	-
Copper	mg/L	32	22%	0.013	0.046	0.0025	355	0.0052	0.262	0.0029	7	22%
Selenium	ug/L	32	100%	0.148	0.21	0.073	142	0.031	1.14	5	0	0%
Zinc	mg/L	32	6%	0.032	0.036	0.025	110	0.057	0.22	0.037	2	6%
Chlorpyrifos	µg/L	32	13%	0.014	0.0077	0.01	55	0.011	0.041	0.015	1	3%
Cyhalothrin, lambda,	µg/L	32	2%	0.010	0.0001	0.01	1	0.011	0.011	35	0	0%
Cypermethrin, total	µg/L	32	2%	0.025	0.0024	0.025	9	0.052	0.052	0.002	1	3%
Dimethoate	µg/L	32	19%	0.096	0.130	0.05	135	0.13	0.69	1.4	0	0%
Diuron	µg/L	32	3%	0.56	0.32	0.5	57	2.3	2.3	10	0	0%
Esfenvalerate/Fenvalerate	µg/L	32	2%	0.010	0.0001	0.01	1	0.011	0.011	-	-	-
Glyphosate	µg/L	31	3%	3.79	1.27	5	34	5	5	700	0	0%
Triclopyr	µg/L	32	3%	0.026	0.0060	0.025	23	0.059	0.059	300	0	0%
Trifluralin	µg/L	32	11%	0.072	0.104	0.05	145	0.068	0.64	17	0	0%

Table 3b. Wet Season Water Quality Monitoring Results (Detected Compounds Only) Water Year 2006

Analyte	Unit	No. of Samples	Detection Rate	Mean	Std Dev	Median	CV	Min	Max	Initial Screen Threshold (IST)	No. of Samples Exceed IST	% of Samples Exceed IST
Temperature	°C	50	100%	13.0	1.8	12.7	14	9.66	19.3	-	-	-
Oxygen, Dissolved	mg/L	48	100%	9.86	4.27	9.5	43	0.11	23.5	<8	11	23%
TSS	mg/L	50	50%	28.8	39.5	7.5	137	10	218	-	-	-
Turbidity (Field)	NTU	50	100%	16.6	30.9	6.45	186	0.68	195	50	3	6%
TDS	mg/L	50	100%	246	172	198	70	12	680	450	8	16%
Specific Conductivity	uS/cm	49	100%	405	382	302	94	50	2380	315	24	49%
Hardness as CaCO3	mg/L	50	100%	123	92	100	74	17.6	413	-	-	-
pH	SU	50	100%	7.94	0.70	7.78	9	6.8	10.2	6.5 - 8.5	8	16%
DOC	mg/L	49	99%	8.58	6.07	7.7	71	0.54	23.8	3	37	76%
TOC	mg/L	49	99%	10.2	7.3	8.3	71	1.5	35.2	3	43	88%
TKN	mg/L	49	100%	3.54	8.07	1.5	228	0.58	55.6	-	-	-
NO_3 + NO_2 as N	mg/L	50	97%	3.41	4.88	1.325	143	0.2	20.1	10	5	10%
Diss. Phosphorus as P	mg/L	12	75%	0.36	0.40	0.26	110	0.14	1.42	0.025	9	75%
Phosphorus as P	mg/L	49	87%	0.956	2.42	0.278	254	0.05	12	0.025	43	88%
Bromide	mg/L	50	8%	0.328	0.309	0.25	94	0.54	1.8	0.05	4	8%
Dissolved Potassium	mg/L	12	100%	6.46	9.13	3.865	141	1.5	34.5	-	-	-
Potassium	mg/L	50	98%	9.8	17.9	4.23	182	1.77	110	-	-	-
Diss. Copper	mg/L	12	17%	0.0034	0.0024	0.0025	71	0.0053	0.0106	0.0027	2	17%
Copper	mg/L	50	47%	0.0075	0.012	0.0025	161	0.0051	0.0749	0.0029	24	48%
Selenium	µg/L	19	100%	0.198	0.165	0.141	84	0.051	0.715	5	0	0%
Zinc	mg/L	50	8%	0.037	0.063	0.025	170	0.0581	0.463	0.037	4	8%
Chlorpyrifos	µg/L	50	2%	0.0250	0.0000	0.025	0	0.025	0.025	0.015	1	2%
Diazinon	µg/L	50	28%	0.070	0.104	0.025	148	0.03	0.5	0.1	8	16%
Diuron	µg/L	37	38%	3.76	14.6	0.5	387	0.4	89	10	2	5%
Glyphosate	µg/L	24	13%	10.8	15.9	5	146	45	56	700	0	0%
Parathion, Methyl	µg/L	50	2%	0.053	0.018	0.05	35	0.18	0.18	0.08	1	2%
Prowl	µg/L	50	16%	0.095	0.160	0.05	168	0.058	0.85	50	0	0%
Triclopyr	µg/L	24	17%	1.75	2.28	1.42	130	0.34	11	300	0	0%
Trifluralin	µg/L	50	2%	0.051	0.0099	0.05	19	0.12	0.12	17	0	0%

SEASONAL EFFECTS IN THE FRAMEWORK AREA

Water quality differences by season (irrigation verses wet season) were examined using two-way analysis of variance analysis (ANOVA). Station and season were used as the effects variables in the ANOVA. A two-way ANOVA design that accounts for the different distribution of sampling stations among seasons was necessary to avoid biasing the results of the analysis based on which stations were sampled in each season.

Statistical analysis was conducted using nonparametric methods (Wilcoxon or Kruskal-Wallis tests) due to the non-normal distribution of the data. Statistical assumptions for ANOVA require that the data are normally distributed and the variance is equal between comparison groups. These conditions were not satisfied for the water quality data from urban runoff. Nonparametric statistical comparison methods (using the ranks of the concentrations data rather than the actual values) were used to transform the data so that these assumptions were achieved. The null hypothesis tested was that stations sampled during both the irrigation and wet seasons were not significantly different. Statistically significant differences between seasons are those where the null hypothesis is rejected, inferring stations are different between seasons. Figure 5 gives the results of the comparison for parameters that showed significant seasonal differences.

Significant seasonal differences were found for TDS, nutrients (nitrate+nitrite, total Kjeldahl nitrogen [TKN], total phosphorus), total organic carbon (TOC), diazinon, and total copper ($p < 0.05$ Wilcoxon rank sums)[5]. For the above parameters wet season concentrations were higher than irrigation season concentrations. No significant seasonal differences were found for TSS or zinc. (A low frequency of detection and differing detection limits for irrigation and wet season samples precluded statistical analysis for chlorpyrifos)

Irrigation season water quality in district canals is generally dominated by the very high quality reservoir releases used as the primary water supply. As this high quality supply water is delivered to growers some other water sources (such as agricultural return flows, groundwater supply wells, groundwater level control wells, and dry weather discharges from urban areas) are added. These other water sources are of lower quality, resulting in decreasing water quality as water flows through the system. Agricultural return flows are generally thought to be a minor component of the water in the canals because many canals are higher topographically than the adjoining ground surfaces under irrigation. In addition, most of the irrigated lands are surrounded by berms. Thus, most growers need to actively pump return flows into the system.[6] At the lower end of the canal system, drainage ditches containing minimal return flows and groundwater level control wells discharge water into the canals. The influence of these wells is clearly seen as elevated TDS concentrations at stations that are downstream of the drainage ditches. During the winter wet season, when irrigation demand is low the canals are not used to deliver irrigation

[5] Note the figures display data on an arithmetic scale while the statistical analysis was performed using nonparametric methods (on the ranks of the data). In some cases figure results (e.g. copper) appear to be inconsistent with the statistical results due to the difference between the figure display and statistical scales.

[6] Irrigation district conveyance facilities in the Framework area include tunnels, open canals, closed pipes, and natural waterways; however, the most common facilities are elevated lined or unlined canals.

water to growers. Instead, the canals are used as the de-facto storm drain system for cities and towns. As a result, nonirrigation flows, including urban runoff, become more dominant. The observed elevated wet season concentrations in the Framework study area samples may reflect this increased contribution of urban runoff with higher concentrations of these constituents as compared to irrigation system flows.

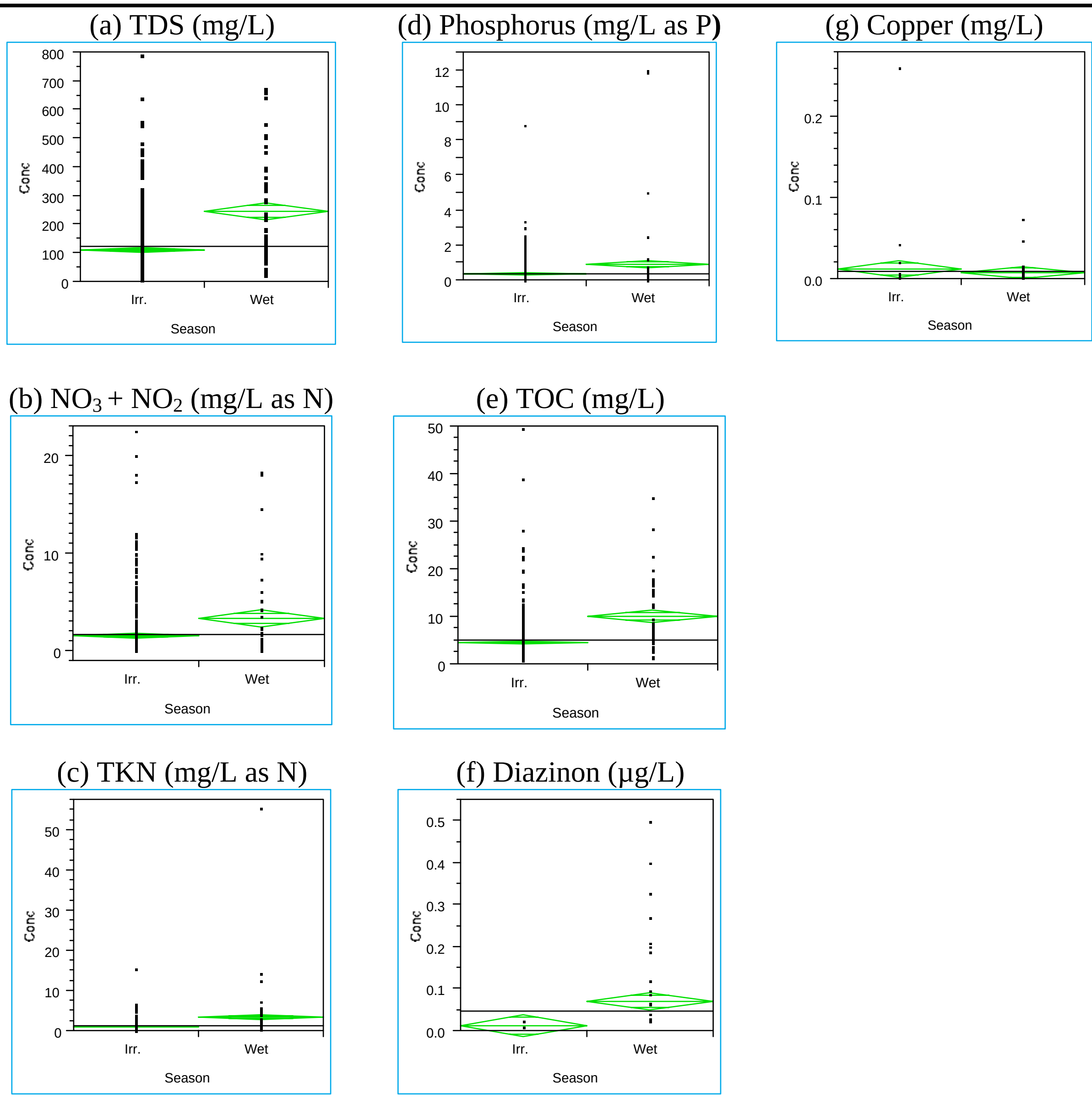


Figure 5. Comparisons of Irrigation and Wet Season Water Quality in Framework Area During Water Year 2006

(Note: diamonds represent mean (middle line) and 95 percent confidence interval of the mean [top and bottom points]. Wet season concentrations were all statistically higher than dry season concentrations [p < 0.05 Wilcoxon rank sums]).

COMPARISON WITH URBAN RUNOFF DATA

A similar analysis was conducted to compare Framework data to urban runoff data. Only wet season urban runoff data were used for the comparison. In general, irrigation (dry) season urban runoff flows are small compared to irrigation deliveries and their influence would be difficult to detect. In addition, most urban runoff programs do not routinely collect or report data on water quality during the dry season unless they are seeking evidence for specific enforcement actions for illicit discharge activities.

Results of the comparisons are shown on Figure 6. The figure shows log-mean concentrations and confidence limits as diamonds of the Framework monitoring data from both irrigation and wet seasons (ESJWQF.Irr and ESJWQF.Wet), for the City of Modesto Stormwater Management Program for the wet season (MMS4.Wet), and for the BASMAA data from the San Francisco Bay Area (SFBAY Area.Wet).

Concentrations in the City of Modesto MS4 (MMS4) data were similar to those measured in the Framework area during the wet season for the following parameters: TSS, nitrate+nitrite, TKN, phosphorous, and zinc. Concentrations of TDS and diazinon were lower in the MMS4 data, while concentrations of copper and zinc were higher in the MMS4 data. TOC concentrations were somewhat higher in the MMS4 data, although not significantly.

Similar or elevated concentrations in MMS4 data suggest that urban runoff, rather than overland runoff from adjacent farms is a major driver for water quality in the Framework area canals during the wet season. Elevated TDS in the Framework samples is likely due to the local hydrogeology and agricultural practices in the lower watershed area of the Framework that results in shallow saline groundwater that can potentially seep into drainage facilities.

Both City of Modesto and Framework wet season data were significantly lower than San Francisco Bay Area urban runoff data for all parameters with the exception of TDS, nitrate+nitrite, TKN, and TOC. Of these parameters, nitrate+nitrite and TKN in MMS4 and Framework wet season samples were higher than Bay Area data, while concentrations of TOC were similar to Bay Area results. Both copper and zinc were quite elevated in Bay Area data as compared to the Framework and MMS4 data, likely due to the more intensive urbanization and dense land use in the Bay Area as compared to the Framework area.

Elevated concentrations of metals are often associated with urban runoff. Copper has been identified as a major component in automotive disk brake pad wear debris (Rosselot 2006) and is a constituent in many herbicides used frequently in the region (both terrestrial and aquatic). Zinc is a major component of galvanized steel, is found in roofing material, and has many transportation- and automotive-related sources including motor oil leaks, diesel fuel, and tire wear debris (ACCWP 1993; Gromaire-Mertz 1999).

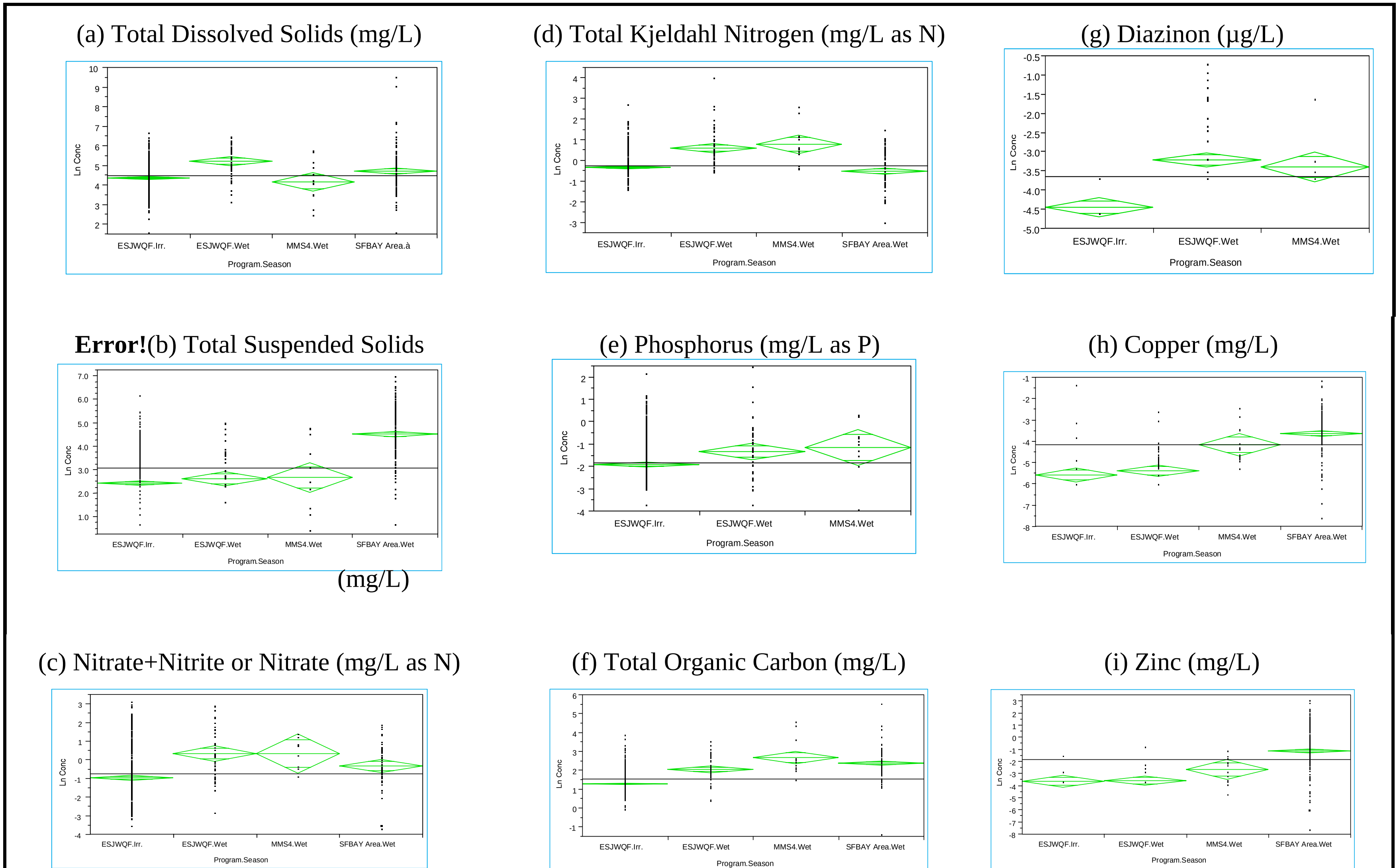


Figure 6. Comparisons of Water Quality in the Framework Area with Wet Season Urban Runoff from Modesto Stormwater Management Program (MMS4) and San Francisco Bay Area

(Concentrations are shown as natural logs of the data. Diamonds represent log-mean [middle line] and 95 percent confidence interval of the log-mean] top and bottom points of diamond].)

SUMMARY

Increasing conversion from agricultural to urban land use is predicted for the San Joaquin Valley. As land use changes, water quality from winter runoff is expected to change reflecting the different nature of activities occurring in the San Joaquin Valley. A large 1-year monitoring program was recently completed as a part of the East San Joaquin Water Quality Framework. Analysis of the Framework data and comparison with urban runoff data suggest that concentrations of nutrients, metals, pesticides, and organic carbon is higher in irrigation district canals during the wet season (which generates a greater proportion of urban runoff) as compared to the irrigation system. These elevated wet season concentrations are due to the lack of high quality irrigation supply water in the canals during the non-growing season, when canals are emptied for maintenance. During the irrigation season this clean supply water serves to dilute non-irrigation water sources. Wet season urban runoff water quality data are similar or higher than water quality data collected in irrigation district systems during the wet season, suggesting urban runoff, rather than farm sources, dominates water quality in the wet season.

Comparison of City of Modesto and Framework wet season water quality with urban runoff data collected by nearby municipal programs in the San Francisco Bay Area indicate concentrations of nutrients are elevated in the Framework area and City of Modesto urban runoff during the wet season compared to ultra-urban areas such as the San Francisco Bay Area. Conversely, concentrations of pollutants such as copper and zinc that have historically been associated with urban sources such as brake pad wear debris and tire wear are higher in urban runoff collected in the San Francisco Bay Area.[7]

Limited data exist for specific sources of water discharged into district canal systems. Specific information on water quality of tailwater, groundwater level control wells, and water supply wells would be helpful in developing control measures to improve water quality. A companion paper (Blankinship et al. 2007) provides some information on tailwater quality generated in a field experiment[8] and best management practices (BMPs). However, little comprehensive information exists on the amount of agricultural lands that have tailwater discharges in the Framework area, making it difficult to develop widely applicable BMPs. A study of actual flows from tailwater and other sources on a monthly or more frequent basis would enable water quality managers to develop revised operational methods and BMPs to improve water quality.

As urbanization continues in the San Joaquin Valley, the MS4 programs will need to implement water quality controls for existing and new development that are effective at controlling target

---

[7] It should be noted that period of record for the San Francisco Bay area urban runoff sources data predates the Framework and Modesto MS4 data by approximately 10 years. Over this time frame the BASMAA agencies have been implementing their BMP-based control programs. However, recent data from the BASMAA were not available to update the database.

[8] Water quality data presented in Blankinship et. al. 2007 was developed to represent the effects of irrigation timing following pesticide application. For the study a field that does not discharge tailwater was used and standing water at the lower end of the field was sampled. As such, the data may not be representative of tailwater quality actually discharged from fields in the Framework study area.

pollutants. Such controls are needed to ensure water quality is protected for current and future beneficial uses.

REFERENCES

Alameda Countywide Clean Water Program (ACCWP). 1993. Annual Monitoring Report FY 91-92. Prepared by Woodward-Clyde Consultants.

Bay Area Stormwater Management Agencies Association (BASMAA) 1996. San Francisco Bay Area Stormwater Runoff Monitoring Data Analysis 1988-1995. Report prepared by Woodward-Clyde Consultants. October. Access online at http://www.basmaa.org/documents/index.cfm?fuseaction=documentdetails&documentID=11.

Blankinship, M.S., L.S. Hunt, J. Edmunds, T. Cooke, and W. Ward. 2007. *East San Joaquin Water Quality Framework: Focused Management Practice Pilot Studies for Prevention of Pesticide Transport to Surface Water.* United States Fourth Annual Conference on Irrigation and Drainage, September 30–October 6.

Domagalski, J.L., and C. Munday. 2003. *Evaluation of Diazinon and Chlorpyrifos Concentrations and Loads, and Other Pesticide Concentrations, at Selected Sites in the San Joaquin Valley, California, April to August, 2001.* Water-Resources Investigations Report 03-4088. U.S. Geological Survey, Sacramento, CA. Prepared in cooperation with the California Department of Pesticide Regulation.

Edmunds, J., L.S. Hunt, T. Cooke, and W. Ward. 2007. *East San Joaquin Water Quality Framework: 2005/2006 Water Quality Monitoring Results.* United States Fourth Annual Conference on Irrigation and Drainage, September 30–October 6.

Gromaire-Mertz, M.C., S. Garnaud, A. Gonzalez, and G. Chebbo 1999. Characterization of Urban Runoff in Paris. *Wat. Sci. Tech*.39 (2):1-8. Access online at http://www.enpc.fr/cergrene/HomePages/mcm/articles/runoff.pdf.

Hunt, L.S., W. Ward, J. Edmunds, T. Cooke, and L.S. Hunt. 2007. *East San Joaquin Water Quality Framework: The Approach.* United States Fourth Annual Conference on Irrigation and Drainage, September 30–October 6.

Rosselot, K.S. 2006. Copper Released from Brake Lining Wear in the San Francisco Bay Area. Prepared for the Brake Pad Partnership. January. Access online at http://www.suscon.org/brakepad/pdfs/BrakeSourcesReportFinal01-30-06a.pdf.

EAST SAN JOAQUIN WATER QUALITY FRAMEWORK: PESTICIDE MANAGEMENT STUDIES ADDRESSING SURFACEWATER QUALITY

M. Blankinship[1]
J. Edmunds[2]
L.S. Hunt[3]
T. Cooke[4]
W. Ward[5]

ABSTRACT

The East San Joaquin Water Quality Framework is located in California's Central Valley and among its objectives is to support the Irrigated Lands Waiver regulatory program and to provide data for proposed Total Maximum Daily Loads (TMDLs). Historically, chlorpyrifos and diazinon have been detected in Framework surfacewater in excess of proposed TMDL objectives. Two studies were performed to address this issue. A chlorpyrifos irrigation study was designed to assess the potential benefit to tailwater quality using extended irrigation lag times. The study artificially induced tailwater drainage in an almond orchard and evaluated tailwater quality using 24 (control), 48, and 72 hour lag times between pesticide application and flood irrigation. Extended lag times significantly improve tailwater quality compared to the control. Airblast sprayers are used extensively in almond and other tree crops for application of a variety of pesticides, including the chlorpyrifos and diazinon. Efficient sprayer operation results in more complete product delivery and distribution in the tree canopy and less product deposited to the ground where it can potentially move to surface water and impact water quality. An airblast sprayer calibration study was done to assess and improve the effectiveness of airblast sprayers in the Framework area. Ten on-site calibrations were completed using Pessl® calibration equipment. Improvements in uniformity and nozzle performance averaged 3% and 8% respectively and pre- and post calibration spray distribution patterns were improved.

LOCATION AND BACKGROUND

The East San Joaquin Water Quality Framework provides a cost-effective watershed organizational structure for cooperative and coordinated water quality improvement activities. Among the Framework's objectives is to support the CalEPA Regional Water Quality Control Board's (RWQCB) Irrigated Lands Waiver ('Ag Waiver") and to provide data for pending RWQCB Total Maximum Daily Loads (TMDLs) for chlorpyrifos and diazinon.

[1] Project Manager, Blankinship & Associates, 322 C St., Davis, CA 95616; blankinship@envtox.com.
[2] Senior Environmental Scientist; URS Corporation, 1333 Broadway, Oakland CA 94612; jody_edmunds@urscorp.com..
[3] Senior Environmental Engineer; URS Corporation, 1333 Broadway, Oakland CA 94612; lisa_hunt@urscorp.com
[4] Manager – Water Environment Department; URS Corporation, 1333 Broadway, Oakland CA 94612; terry_cooke@urscorp.com.
[5]Assistant General Manager – Water Operations; Modesto Irrigation District, P.O. Box 4060, Modesto, CA 95352; walterw@mid.org.

The Framework study area is located in the San Joaquin Valley on the east side of the San Joaquin River east of San Francisco and south of Sacramento. The major tributaries that transect the area are the Merced, Tuolumne, and Stanislaus Rivers, the combination of which delivers an average of 66 percent of the San Joaquin River's annual flow (Domagalski and Munday 2003). The study area encompasses approximately 600,000 acres, including areas served by five irrigation districts: Turlock, Modesto, South San Joaquin, Merced, and Oakdale. Refer to Figure 1.

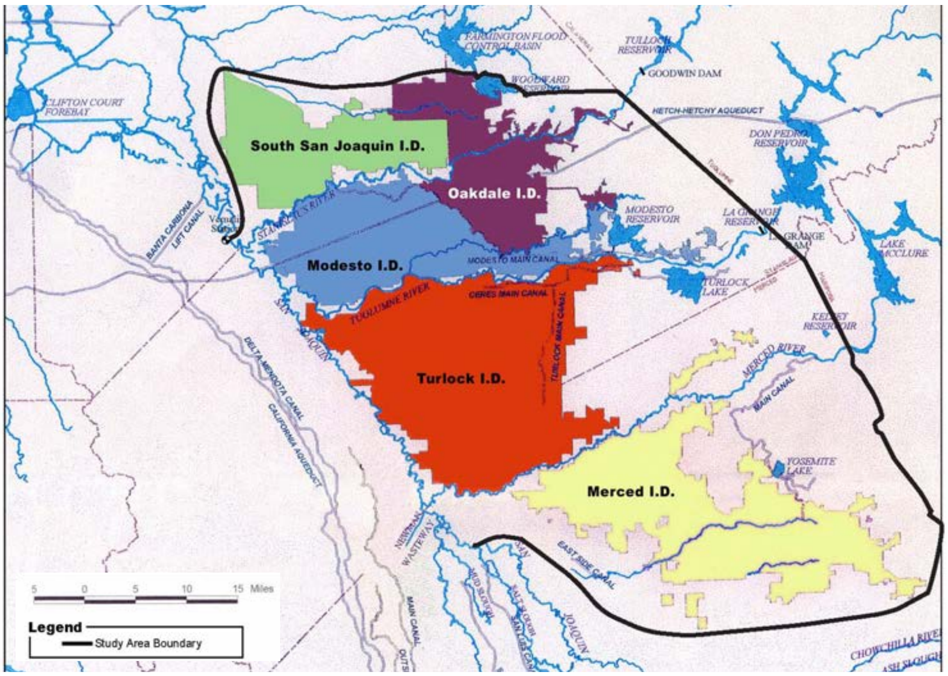


Figure 1. Project Area

The Framework addresses both urban and agricultural sources of water quality (Cooke et al 2007). The goal of the Framework is to develop and implement a comprehensive program that accomplishes the following:

- Supports compliance with the Irrigated Lands Program requirements (required by the Central Valley Regional Water Quality Control Board since 2003)
- Supports data collection and implementation activities for TMDL projects currently under way
- Provides for development of data on potential water quality problem areas
- Provides information to begin to differentiate among sources (agricultural, urban, dairies, etc.) and focus future monitoring efforts
- Evaluate and suggest for implementation management practices and other control actions that improve water quality

Based on the needs identified by this process, the Framework funded and carried out two pilot studies focusing on reducing the transport of pesticides to surface waters within the Framework area. These two pilot studies are described herein.

PILOT STUDY #1: CHLORPYRIFOS IRRIGATION STUDY

In March 2006, URS prepared a document titled *Outreach and Management Practice Recommendations for the East Sun Joaquin Water Quality Framework Grant Agreement No. 04-1* 72-555-0 (URS 2006a). This document provided specific recommendations for the 2006 Outreach Program and Management Practice Program. It noted that water quality issues associated with diazinon and chlorpyrifos applications represent the most well documented impacts to surface water bodies in the Framework study area.

The best time to treat some insects that interfere with crop production with an organophosphate pesticide is during their dormancy period. Beneficial arthropods are less affected during the dormant period and certain other pests can also be controlled at that time. Also, coverage of the bark is better for control of the overwintering larvae and scale, and less conflict occurs with other cultural practices. Common organophosphate pesticides include diazinon and chlorpyrifos. Based on 2004 data, more than 131,000 lbs of chlorpyrifos and 26,000 lbs of diazinon were used as both dormant and in-season sprays on a variety of crops within the study area.

Dormant sprays are applied between November and January, avoiding spraying close to bloom time due to toxicity to honey bees. However, the dormant season is also the rainy season in California, allowing the organophosphates to sometimes wash off the almond trees and potentially find their way into surface waters (NFIPME 1999, CURES 2002a, CURES 2002b).

Numerous studies have shown that peak concentrations of chlorpyrifos and diazinon in surface waters are correlated with dormant spray periods in orchards during the rainy season (RWQCB 2005). The correlation of peak concentrations with dormant spray periods is stronger for diazinon than for chlorpyrifos, which tends to be associated more with growing-season uses (Poletika 2006).

Although these pesticides have also been widely used for nonagricultural and residential pest control in the past, residential use is being phased out and diazinon and chlorpyrifos are no longer available for sale to residential users (RWQCB 2005). Most nonresidential urban uses of diazinon and chlorpyrifos are no longer permitted, with the exception of some "low risk" uses of chlorpyrifos for railroad boxcars, industrial plants, manufacturing plants, food processing plants, golf courses, road medians, treatment of utility poles and other outdoor wood products, fire ant mounds, and mosquito control.

Based on the above, the recommendations stated that management practice pilot studies for 2006 should focus on agricultural use of chlorpyrifos and/or diazinon (URS 2006a). Based on feedback from stakeholders and discussions with other researchers, chlorpyrifos irrigation timing was chosen as a specific candidate pilot study.

Chlorpyrifos in Surface Water in the Central Valley

The organophosphate pesticide chlorpyrifos has been detected in both the main stem and tributaries of the San Joaquin River at concentrations that exceed California Department of Fish and Game's Water Quality Criteria (WQC). As a result, the San Joaquin River is on the Federal Clean Water Act's 303(d) list as impaired for chlorpyrifos (RWQCB 2002).

The existing Water Quality Control Plan for the Sacramento River and San Joaquin River Basins (Basin Plan) contains only narrative and not quantitative water quality objectives for pesticides and for toxicity. The RWQCB uses available guidelines and criteria to interpret existing narrative water quality objectives. To better regulate point source and nonpoint sources of pesticides the RWQCB has prepared amendments to the Basin Plan for the control of diazinon and chlorpyrifos runoff into the lower San Joaquin River (RWQCB 2005). The amendments identify numeric water quality objectives and TMDLs for diazinon and chlorpyrifos. The WQC were defined in the amendments using California Department of Fish and Game and U.S. Environmental Protection Agency methodologies and are listed in RWQCB Resolution No. R5-2005-0138. The WQC for chlorpyrifos in fresh water are:

- Acute criterion = 0.025 microgram per liter (ug/L) (1-hour average)
- Chronic criterion = 0.015 ug/L (4-day average)

Additionally, the California Department of Pesticide Regulation (DPR) has placed chlorpyrifos into reevaluation with the intention of reducing chlorpyrifos loading enough to meet proposed TMDL target values (DPR 2004).

In 2002, 430,600 pounds of chlorpyrifos were applied in the San Joaquin Valley. The predominant crops that utilized chlorpyrifos were nuts, alfalfa, and cotton (DPR 2002). A recent review (Spurlock 2004) of surface-water detections during 2002 indicates that WQC in the watershed were most frequent in the months of March through August, with March being the highest. Nearly 50 percent of March 2002 applications of chlorpyrifos were made in alfalfa. Additionally, studies (i.e., Long 2002; Poletika and Robb 1998) indicate that tailwater runoff (irrigation surface runoff) from chlorpyrifos applications to alfalfa potentially contribute to WQC exceedances in the watershed.

Due to surface-water quality issues, recent supplements to the diazinon and chlorpyrifos labels call for increased application restrictions. The main substantive label changes for nut crops and alfalfa include:

- No flooding of irrigated field or orchard within 24 hours following an application of Lorsban-4E
- Elimination of retreatment intervals of less than 10 days
- Limit maximum seasonal rate to 8 pints per acre for all nut crops (previously 16 pints per acre)
- Limit maximum seasonal applications to 3 (previously 4)
- Require spray drift buffer zones (150 feet downwind aerial, 25 feet downwind ground)

Chlorpyrifos Use Within the Framework Area

URS (Hunt et al 2007; Edmunds et al 2007) has compiled a database of recent (2000-2005) surface-water quality monitoring data collected in the Framework region under various programs. The programs include, but are not limited to, the RWQCB TMDL programs, U.S. Geological Survey (USGS) pesticide monitoring, irrigation district monitoring, University of California, Davis toxicity monitoring, Ag Waiver, agricultural suitability, National Pollutant Discharge Elimination System permits, RWQCB's Surface Water Ambient Monitoring Program, California Department of Water Resources, and DPR.

According to DPR records from 2000-2004, the amount of chlorpyrifos applied to agricultural fields varies by month, with May and July applications being the highest. The agricultural application rate has not decreased in the last 5 years. The monthly application of chlorpyrifos to different crops within the Framework area in 2004 is shown in Figure 2.

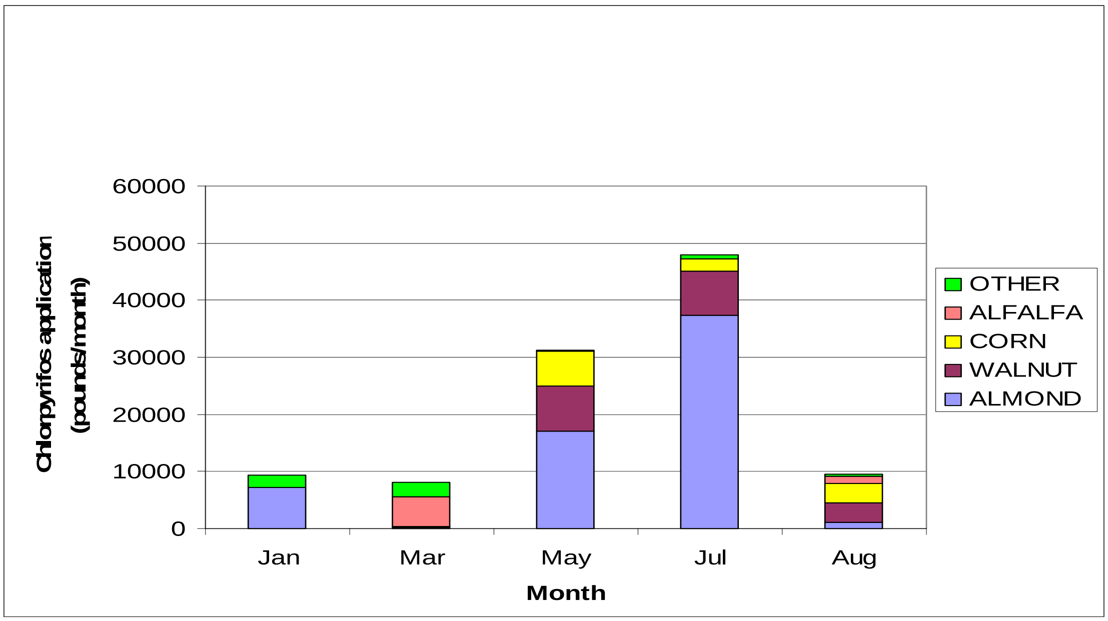


Figure 2. Agricultural Uses (by Crop Type) of Chlorpyrifos in Framework Area in 2004

Only agricultural and professional pesticide use is reported to the County Agricultural Commissioners and made available by the DPR. Therefore, it is difficult to quantify nonagricultural pesticide use, much of which is residential. For example, some nonagricultural pesticide use, such as applications made by professionals, is included in the DPR data.

Pilot Study Objectives

The purpose of this pilot study was to evaluate the extent to which chlorpyrifos moves off almond orchards after irrigation. Specifically, it was to compare differences in chlorpyrifos concentrations in tailwater when irrigation water is applied to the treated field 24, 48, and 72 hours after chlorpyrifos application. Current product label language prohibits irrigation until 24 hours after treatment. The adequacy of this prohibition and its effectiveness in protecting surface-water quality is well understood and a better understanding of chlorpyrifos movement after irrigation may be useful in supporting or modifying future product label language.

Initially, alfalfa was considered for the pilot study. However, based on the pesticide use data presented earlier, chlorpyrifos use on alfalfa is relatively low during the irrigation season. Chlorpyrifos use on alfalfa within the Framework area is highest in March, prior to irrigation. Because most chlorpyrifos use in summer occurs on almond orchards, an almond orchard was selected as the pilot site.

Site Description

A 10-acre almond orchard located was selected in Hughson, California. The orchard is approximately 900 feet by 500 feet. The almond trees are 3 years old and are of the Butte and Padre variety (alternating rows). The orchard has 22 rows of trees (west to east) and 52 trees (north to south). The orchard is normally gravity flood-irrigated every 14 to 21 days from six irrigation turnouts at the northern end of the rectangular plot. The water travels from the northern to the southern end of the plot. The entire perimeter of the orchard is bermed to contain the irrigation water in the orchard. During a normal irrigation event, it takes approximately 2 hours for the water to flow from the irrigation outlets to the southern end of the orchard. The water stays ponded on the orchard floor for 24 to 48 hours before it infiltrates completely. Figure 3 is an illustration of the site layout.

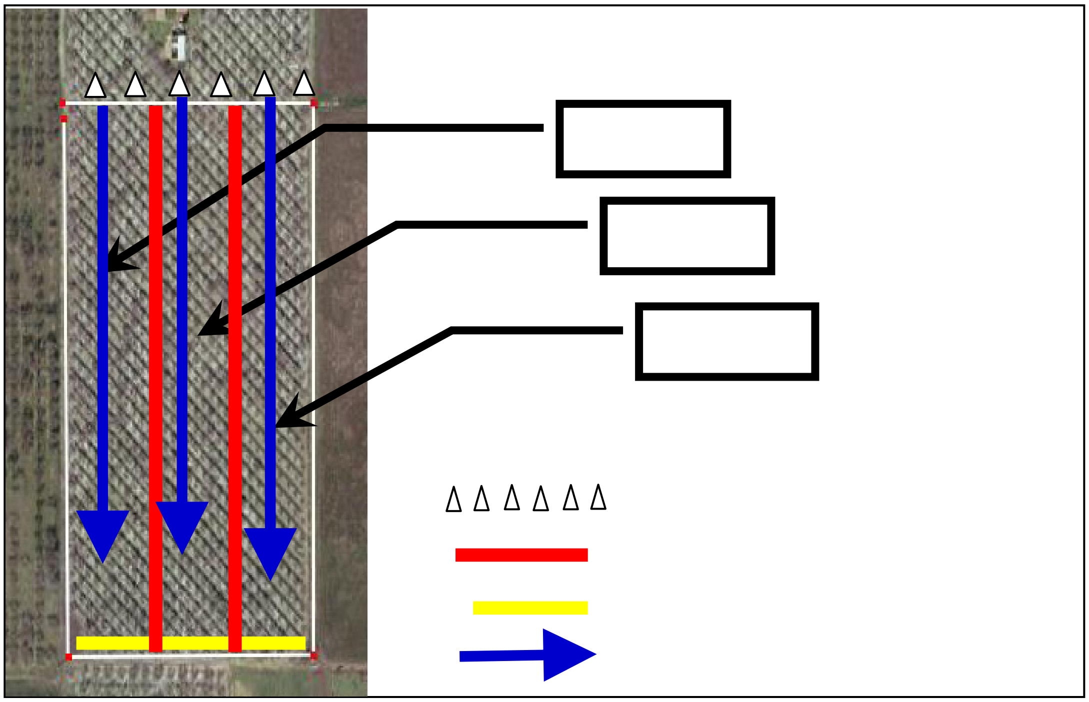


Figure 3. Site Layout

Study Method and Execution

The study was performed from July 25 to 27, 2006 following a detailed workplan (URS 2006b). The DPR, the Coalition for Urban and Rural Environmental Stewardship (CURES), and Dow Agrosciences reviewed and provided comments on the study design. The work plan included the following tasks:

- Divide the orchard evenly into 3 plots using earthen berms to prevent irrigation water from moving from one plot to another.
- Apply chlorpyrifos to the three plots with a foliar application of Lorsban-4E at 2 quarts per acre using an air blast sprayer during control hull split (UCCE 2002).
- Measure chlorpyrifos ground deposition rate using mass deposition sheets.
- Irrigate Plot 1 24 hours after the chlorpyrifos application
- Irrigate Plot 2 48 hours after application.
- Irrigate Plot 3 72 hours after application.
- Measure flow and volume of irrigation water entering each of the plots
- Collect samples of the water in the furrow at the tail end of each plot.
- Analyze samples for chlorpyrifos, total organic carbon and total suspended solids assuming that they are representative of any tailwater at the end of the field.

Water flow measurements were made by CalPoly San Luis Obispo Irrigation Training and Research Center staff using temporary orifices and weirs in existing irrigation turnout structures, a SonTek® Flow Tracker in 30-inch supply pipeline and a MARSH McBirney FLO-MATE® flow meter in the orchard (ITRC 2006). Flow rate measurement at weir-type turnouts was done using Weir Stick and flow rate measurement at orifice-type turnouts using field-calibrated orifice equation.

Four water samples were collected from each plot in the furrow at the end of the plot and one irrigation water sample was collected from each irrigation water turnout source before being applied to the orchard. The tailwater sample was representative of irrigation water that had passed through the orchard and would be runoff leaving the orchard if the orchard did not have a perimeter berm. Note that this field had a field berm and no runoff water left the site.

Results

Soil All of the soil samples were classified according to Unified Soil Classification as silty sand except the southeastem corner of the orchard (Plot 3 southern end) which was classified as silty, clayey sand. The three plots have an average TOC concentration of 671 milligrams per kilogram (mg/kg) (standard deviation = 116). Soil organic matter adsorbs many pesticides. Pesticide mobility may be expected to be greater in soils having low TOC as compared to soils having high TOC. The composite soil samples from the three plots were analyzed for Chlorpyrifos.

Three samples were collected from each plot and analyzed for chlorpyrifos deposition after airblast sprayer application. One duplicate sample was also collected from Plot 2 and one blank sheet was submitted for analysis. The average ground depositions for Plots 1, 2, and 3 were 57.1, 60.8, and 62.7 grams/acre (g/ac), respectively. The average deposition rate was 61.5 g/ac (Standard Deviation = 8.3) suggesting reasonable and acceptable chlorpyrifos application uniformity.

Irrigation Water Analysis of irrigation water coming from the turnouts reported concentrations of chlorpyrifos that ranged from .012 to 0.12 ug/L. Plot 2 results showed nondetect (<0.003 ug/L) chlorpyrifos concentrations. The detected concentrations could be from pesticide deposited on the irrigation turnout. Total organic carbon (TOC) concentrations ranged from 1.6 to 3.7 mg/L and were relatively consistent between the three plots. Total suspended solids (TSS) concentrations were all nondetect. Analyte methods and detection limits are summarized in Table 1.

Table 1. Summary of Analytes, Methods, and Detection Limits

Analyte	**Method**	**Detection Limit**
Chlorpyrifos	EPA 8141A	.00259 ug/L
TSS	EPA 160.2	1.18 mg/L
TOC	EPA 415.1	.13 mg/L

Tailwater Tailwater samples were collected as soon as the irrigation water reached the furrow at the southern end of the orchard. For Plot 3, the water arrived 2 hours and 2 minutes after the start of irrigation. Plot 2 irrigation water reached the southern end of the orchard 3 hours and 46 minutes after the start of irrigation, and Plot 1 irrigation water reached the southern end of the orchard 2 hours and 18 minutes after the start of irrigation.

Table 2 is a summary of tailwater chlorpyrifos analytical results and Figure 4 is a graph of chlorpyrifos concentration vs. time. These results indicate that delaying the application of irrigation water results in lower concentrations of chlorpyrifos in the tailwater.

Table 2. Summary of Chlorpyrifos Tailwater Concentration Data

Plot	**Lag Time (hrs)**	**Tailwater Conc (ug/L)**	**% Reduction from Baseline**
3	28	11	Baseline
1	51	5.0	55%
2	81	3.1	72%

Temperature, conductivity, pH, and dissolved oxygen did not vary significantly among the three plots. A trend or change in TOC over time does not appear to occur due to irrigation times. TSS concentrations were very sporadic and did not show a trend over time due to irrigation.

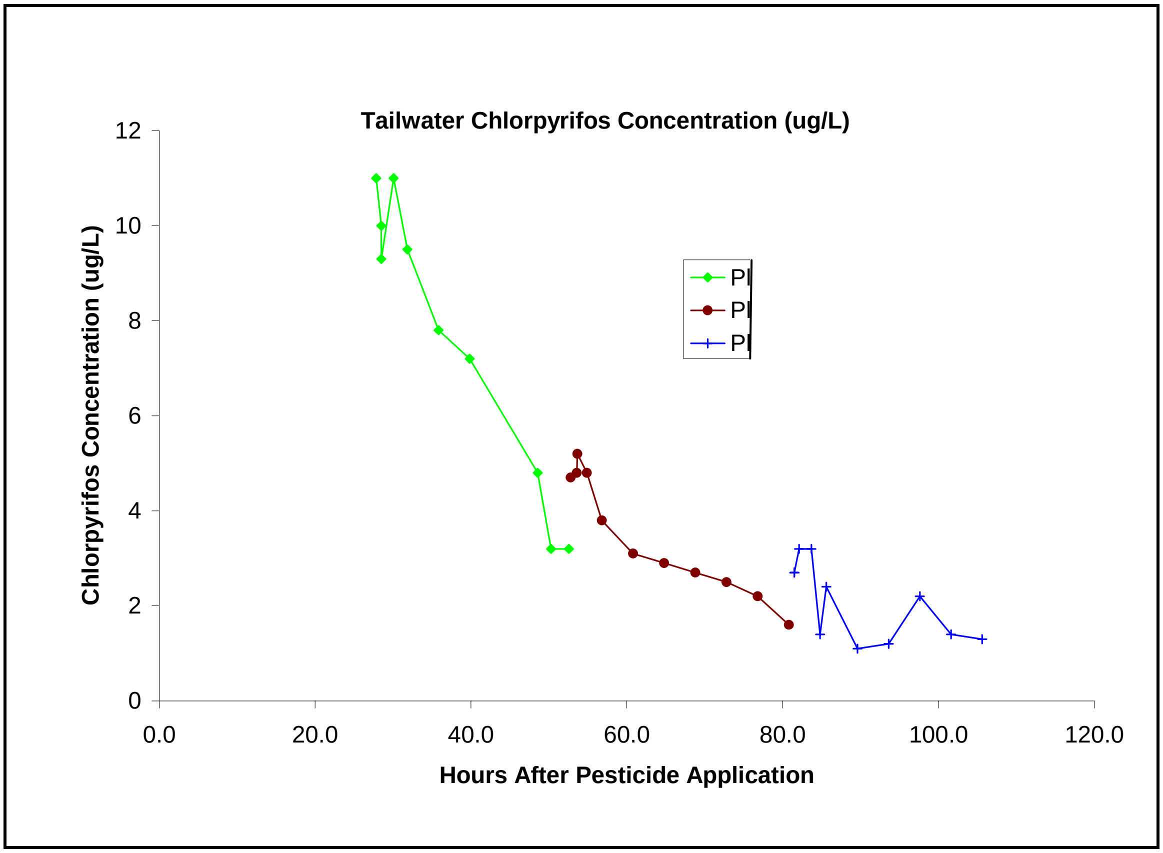


Figure 4. Tailwater Chlorpyrifos Concentration (ug/L)

Conclusions and Recommendations

The orchard proved to be a suitable site for this pilot study. The soils were of the same or similar type and all three plots had the same irrigation water source. Chlorpyrifos application rate was similar for all three plots as determined by the deposition analysis. No irrigation water runoff left the site. However, the site can be considered a reasonable surrogate almond orchard to evaluate runoff if it were to occur. Therefore chlorpyrifos concentrations measured in tailwater collected from this site are likely reasonably representative of tailwater from other orchards with similar conditions if irrigation occurs soon after Chlorpyrifos application.

The results of this pilot study show that delaying the irrigation time to more than a 24-hour period after pesticide application result in a significant reduction in chlorpyrifos in tailwater. However, because of the limited size, scope, and statistical power of this preliminary study, no broad conclusions can be made and it is recommended that additional studies be conducted to verify the results and gather additional information. Some recommendations for additional studies include the following:

- Include application irrigation intervals longer than 72 hours to determine the time necessary to reduce chlorpyrifos concentrations in tailwater below the TMDL standards
- Include additional sites representative of orchards in the region

- Evaluate the percentage of orchards in the region that are likely to actually have tailwater runoff flowing to a ditch or surface water body. Evaluate whether certain crop types do or do not have tailwater runoff
- Include multiple plots and events to provide additional statistical power.

PILOT STUDY #2: SPRAYER CALIBRATION STUDY

Background and Approach

Airblast sprayers are widely used in production agriculture to apply chemicals to tree canopies. These sprayers are towed behind farm tractors and introduce a liquid pesticide or fertilizer into a fast-moving stream of air directed up and into the tree canopy and the air blast carries the material into the tree canopy. The degree to which this technique is effective is dependent on numerous factors including the operational capability of the sprayer.

Growers who were interested in participating in the sprayer calibrations and consultations were identified and contacted by Blankinship & Associates, Inc. Pesticide sprayer calibrations and grower consultations were then conducted within the Framework area with equipment and personal assistance from the Coalition of Urban/Rural Environmental Stewardship (CURES).

A total of ten sprayers used in almond, walnut and peach orchards were calibrated in August of 2006.

Calibration Equipment

Nozzle Output Calibrations The sprayer calibration unit was obtained from Pessl Instruments, GmbH (Weiz, Austria), and was used to conduct the nozzle output tests during the calibrations. The instrument has hoses that are attached to the sprayer nozzles, which confines any output to the test system. When the sprayer is turned on, the spray emitted by the individual nozzles is carried through the hoses to tubes (one for each nozzle) where sensors measure the nozzle output in gallons per minute and transmit the data to the computer. Refer to Figure 5.

Figure 5. Pessl Airblast Sprayer Calibration Equipment

Vertical Distribution Calibrations The Pessl unit was also used to conduct an analysis of the vertical distribution of spray during the calibrations. The instrument consists of a 4-foot wide by 15-foot tall screen stand with spray collectors on the back. The spray emitted from the spray rig onto the stand is collected in tubes with sensors that measure the amount of spray applied at each height above the ground. The sensors send the data to the computer, which creates a graph of the vertical distribution of spray and overlays that graph on an image of an average tree specific to the grower's crop. The two sides of the boom must be tested separately, and the computer program combines the data from both sides on the graph. Refer to Figure 6.

Methods

Nozzle Output Calibrations An initial test of the nozzle output was conducted to assess what needed to be done during the calibration to improve the output performance and the uniformity of output on the left and right sides of the boom. In the "before calibration" graph, some of the nozzle outputs are red rather than blue to indicate that the output is not within the range of the manufacturer's specifications for that nozzle. The variation in spray distribution between the left and right sides is also evident in the before graph. Based on those initial output data, the calibration technician cleaned out clogged strainers in the nozzles and/or on the tank and replaced damaged or missing parts as necessary and feasible. After completing the maintenance work on the nozzles, the technician used the Pessl instrument to measure the "after calibration"

Figure 6. Pessl Airblast Sprayer Calibration Equipment

nozzle output and uniformity of output across the boom. If certain nozzles continued to have unacceptable output, the technician would make further adjustments/repairs to the nozzles.

Calibrations were conducted on sprayers with varying numbers of booms and varying numbers of nozzles per boom. The Pessl instrument is designed to test up to 16 nozzles on a boom. Thus, each boom was calibrated separately, and booms with more than 16 nozzles required more than one set of tests.

Vertical Distribution Calibrations An initial test of the vertical distribution of spray relative to the sample tree shape was conducted. The calibration technician assessed the nozzle angles and/or the angle of the fins. Nozzle and fin adjustments were made to direct spray on the tree foliage, thereby reducing spray above and below the canopy. After making the necessary adjustments, the technician conducted an “after calibration” test to reassess the vertical distribution of the spray into the tree canopy.

Results

Some of the sprayers that were calibrated had multiple booms designed for different output volumes and/or for different crops. During the calibrations the technician was able to measure the performance for each boom on a sprayer. Thus, the data are grouped by boom rather than by sprayer.

While conducting the calibrations, the calibration technician recorded the work he performed, including cleaning out clogged strainers in the nozzles, adjusting the angle of the nozzles, fins and scoops, and replacing damaged or missing parts as necessary and feasible to improve the efficiency of the nozzle output and vertical distribution of spray over the tree canopy. A summary of adjustments and replacements made during the various calibration tests is provided in Table 3.

Table 3. Summary of Airblast Sprayer Adjustments and Replacements

Description of Parts Cleaned, Adjusted, or Replaced	**Cleaned, Number of Parts Adjusted, or Replaced**
Nozzle Discs Replaced (tips)	20
Nozzle Cores Replaced (piece behind tip)	10
Strainers Cleaned	41
Strainers Added/Replaced	1
Nozzles Adjusted For Angle Of Spray	5
Nozzle Bodies Cleaned	5
Fins and Scoops Adjusted For Angle Of Spray	15

Nozzle Output Performance The nozzle output performance (OP) was calculated by comparing the measured output to the manufacturer’s specification for nozzle output using the following equation:

OP= Measured Nozzle Output (gpm)/Manufacturer’s Nozzle-specific Design Output (gpm)

The goal is to have 100% of the manufacturer’s specification output for each nozzle. Nozzle output above or below 100% of the manufacturer’s specification output could have negative impacts on the spray application efficiency. If the output is greater than 100% of the manufacturer’s specification output, that nozzle is emitting too much spray and may result in uneven distribution of spray on the tree foliage and less effective pest control. If the output is less than 100% of the manufacturer’s specification output, that nozzle is not emitting enough spray and may result in poor spray coverage on the tree foliage and less effective pest control. An example of nozzle output performance improvement is shown in Figure 7.

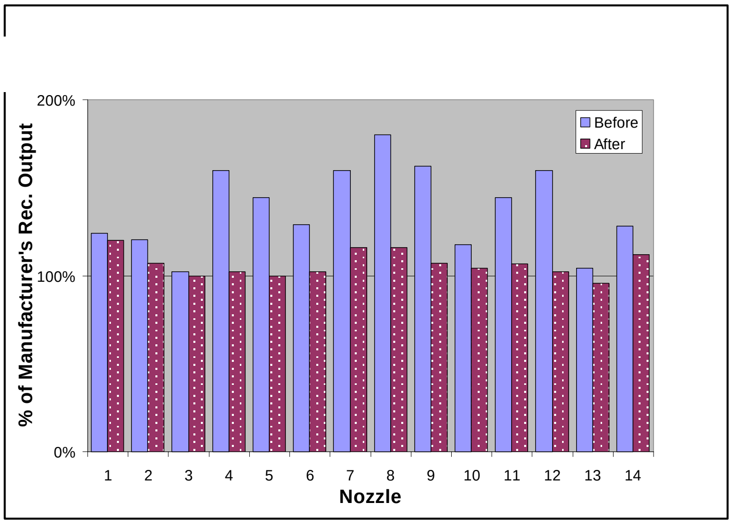


Figure 7. Example of Nozzle Output Performance [Mid 80's Air-O-Fan (14 Nozzles)]

Nozzle performance improvements ranged from 0.5 to 31.5% with an average improvement of 8%.

Uniformity of Output Across the Boom The output of spray was measured and calibrated on the left and right sides of every boom to across the boom. The goal is to have 50% output on each side of the boom, so the improvement in uniformity is relative to 50%. Since the total output is always 100%, whenever there is an increase in output on one side of the boom there must be an equivalent decrease in output on the opposite side of the boom. Thus, the improvement in uniformity can be accurately calculated by looking at the change in output on one side of the boom. Improvements in uniformity ranged from 0.2 to 8.2% with an average of 3%. An example of improvements as a result of improving output uniformity is shown in Figure 8.

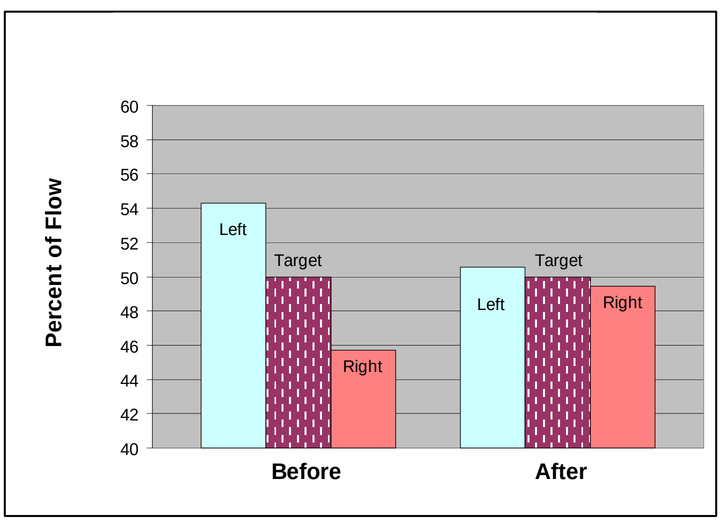


Figure 8. Example of Changes in Right vs. Left Uniformity (2000 Air-O-Fan)

Vertical Distribution Calibration Figure 9 illustrates the vertical distribution data collected before and after the calibration. The green lines represent the average shape of a tree for the grower's orchard type, and the blue line represents the distribution of spray from the sprayer onto the tree (measured on the instrument stand for this test). Note that after calibration, significantly less over and underspray were detected.

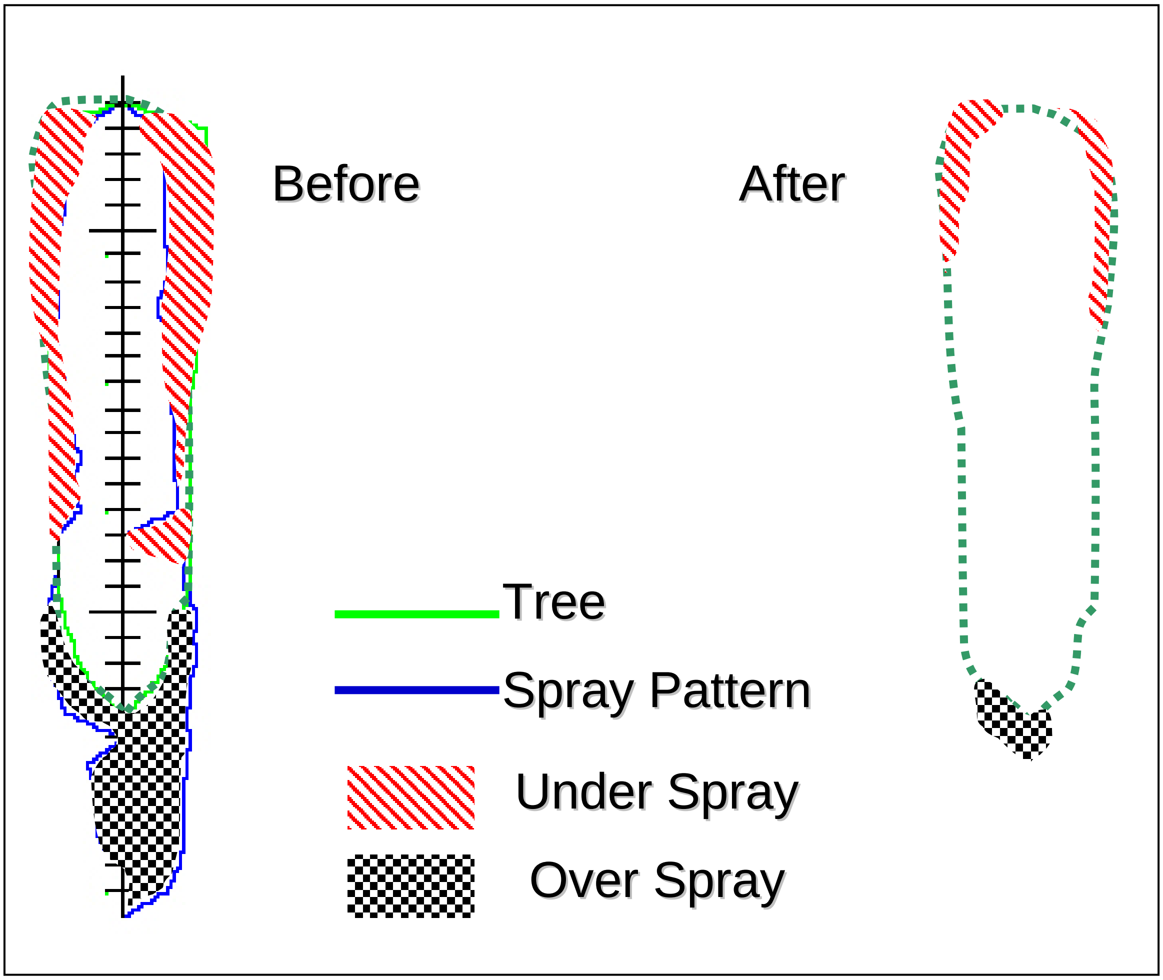


Figure 9. Vertical Spray Distribution Patterns Before and After Calibration

Discussion and Conclusions

The benefits of the calibrations and consultations include improved economic efficiency for growers and the implementation of best management practices to reduce offsite movement of pesticides into the environment. The sprayer calibrations resulted in improved sprayer performance with regard to nozzle output performance, uniformity of spray discharged across the boom, and the distribution of pesticide over the tree canopy. Additionally, the consultations with growers produced an increased understanding of the importance of and procedures for calibrating their sprayers, as well as other best management practices specific to their crops.

In many cases worn nozzle discs were replaced, which reduced or eliminated excess spray from being applied and saved the grower money that would otherwise spent on unneeded pesticide. In other cases, clogged nozzle strainers were cleaned and/or replaced, significantly increasing the flow of spray through the nozzles onto the crops for more effective coverage.

Improvements made to the vertical distribution focused the spray on the crop foliage, which results in better pesticide coverage, reduced spray drift and reduced spray being applied inadvertently to the ground below the tree crops. The reduction of spray above and below the canopy will also reduce the load of pesticides in storm water and irrigation runoff entering local surface waterways and reduce pesticide inputs to waterways from drift. In addition, the increased coverage on the foliage will result in more effective, longer lasting pest control, which may reduce the number of sprays needed per year and reduce the input of pesticides into the environment. Although not quantified, a reduction in the number of sprays needed per year will likely result in potentially significant cost savings for the grower.

Growers were educated about checking sprayer nozzles and orifices regularly for clogging and damage, about cleaning screens frequently, and about filtering mix water if drawn from a source with heavy particulate loads. Other BMPs discussed included always following label directions, wearing personal protective equipment, and turning the sprayer off when making turns and when near sensitive areas. Booklets containing descriptions of best management practices were also provided to the growers. The additional information about calibrations and other best management practices provided to growers during the calibration consultations further support the outreach and education goals of the East San Joaquin Water Quality Framework, CURES, and the State Water Quality Control Board.

REFERENCES

California Department of Pesticide Regulation (DPR). 2002. *Draft Pesticide Use Report Data Summary, 2002.* Available online: http://www.cdpr.ca.gov/index.htm.

California Department of Pesticide Regulation (DPR). 2004. *Notice to Registrants # 2004-4, Notice of Decision to Begin Reevaluation of pesticide Products Containing Chlorpyrifos.* Available online: *http://www.cdpr.ca.gov/docs/canot/cainenu.htin.*

California Regional Water Quality Control Board, Central Valley Region (RWQCB). 2002. *Agricultural Practices and Technologies.* Draft Report. Compiled by E. Reyes and M. Menconi. May.

California Regional Water Quality Control Board, Central Valley Region (RWQCB). 2005. *Amendments to the Water Quality Control Plan for the Sacramento River and Sun Joaquin River Basins for the Control of Diazinon and Chlorpyrifos Runoff into the Lower San Joaquin River.* Final Staff Report. Sacramento, CA. October.

Coalition for Urban/Rural Environmental Stewardship (CURES). 2002a. *Orchard Practices for Protecting Surface Water.* Water Steward, Sacramento and Feather Rivers.

Coalition for Urban/Rural Environmental Stewardship (CURES). 2002b. *Orchard Air Blast Sprayers: Tips and Techniques.*

Cooke, T., L.S. Hunt, J. Edmunds, W. Ward. 2007. *East San Joaquin Water Quality Framework: Urban Water Quality Issues in an Agricultural Region.* United States Fourth Annual Conference on Irrigation and Drainage, September 30 – October 6.

Domagalski, J.L., and C. Munday. 2003. *Evaluation of Diazinon and Chlorpyrifos Concentrations and Loads, and Other Pesticide Concentrations, at Selected Sites in the San Joaquin Valley, California, April to August, 2001.* Water-Resources Investigations Report 03-4088. U.S. Department of the Interior, U.S. Geological Survey, Sacramento, CA. Prepared in cooperation with the California Department of Pesticide Regulation.

Edmunds, J., L.S. Hunt, T. Cooke, W. Ward. 2007. *East San Joaquin Water Quality Framework: 2005/2006 Water Quality Monitoring Results.* United States Fourth Annual Conference on Irrigation and Drainage, September 30 – October 6.

Hunt, L.S., Ward, W., Edmunds, J., T. Cooke, 2007. *East San Joaquin Water Quality Framework: An Approach.* United States Fourth Annual Conference on Irrigation and Drainage, September 30 – October 6.

Irrigation Training and Research Center (ITRC). 2006. Technical Memorandum. Olivas Almond Orchard Evaluation Site Visit Report: July 23, 2006, through July 27,2006. California Polytechnic State University. August.

Long, R. 2002. Insecticide Choice for Alfalfa May Protect Water Quality. California Agriculture. Sept-Oct, 2002 p.163.

National Foundation for Integrated Pest Management Education (NFIPME). 1999. (http:llwww.pesp.orgil999/almond99-fmal.htm)

Poletika, N. and C. Robb, 1998. A Monitoring Study to Characterize Chlorpyrifos Concentration Patterns and Ecological Risk in an Agriculturally Dominated Tributary of The San Joaquin River. Dow Agro Sciences Study ENV96055.

Poletika N. 2006. Personal Communication with Nicholas N. Poletika, PhD, Field Exposure and Effects Regulatory Laboratories, Dow AgroSciences LLC. July.

Spurlock, F. 2004. *Analysis of Recent Chlorpyrifos Use and Surface Water Monitoring Data Department of Pesticide Regulation Policy Memo.* Available online: *http://www.cdpr.ca.gov/docs/sw/policies.htm.*

University of California Cooperative Extension (UCCE). 2002. *Management Decision During Hull Split in Almonds.* Kern County. June.

URS Corporation. 2006a. *Outreach and Management Practice Recommendations for the East San Joaquin Water Quality Framework Grant Agreement No. 04-1 72-555-0.* Prepared for the San Joaquin River Group Authority. March.

URS Corporation. 2006b. *Chlorpyrifos Irrigation Pilot Study Work Plan for the East San Joaquin Water Quality Framework.* Prepared for the San Joaquin River Group Authority. June.

STUDY ON OPERATION OF A LONG DISTANCE WATER TRANSFER CANAL SYSTEM

Wang Changde[1]
Yao Xiong[2]
Fan Jie[3]
Guan Guanghua[4]

ABSTRACT

Long distance water transfer projects are widely used for inter-basin water diversions in China. For large water transfer canal systems, automatic operation techniques are necessary. The middle route of the South-to-North water diversion project is the longest open channel in China. It has a flat slope and a large design discharge, but lacks necessary in-line water storage. For the purpose of supplying accurate amounts of water on demand at the right time, the canal system operation method and control algorithm for the project were studied and a simulation model including siphons, aqueducts, and turnouts was constituted. As an example, the simulation of automatic operation of the emergency sector of the South-to-North water diversion project was carried out and the results showed that the operation of constant volume control method is better than the operation of constant downstream water depth control. The results provide a technical foundation for the automatic control and management of long distance water transfer canal systems, especially the South-to-North water diversion project.

INTRODUCTION AND BACKGROUND

Typical waste in a conventionally operated canal system is about 5 to 10 percent of the total inflow (Burt, 1987). Oftentimes, surplus is wasted at the downstream end of the system. On the other hand, the practice of effective operation of automatic controlled canal systems can significantly cut down the water loss and improve the management of the channels. The South-to-North water diversion project is a strategic infrastructure project of China that is crucial for the regions of northern China, which has a great shortage of water. It is quite important to insure and enhance the economic development, environmental improvement, and social stability of these regions. The middle route of the project, with 1276 km of canals, has complicated water supply targets but lacks the necessary in-line storage. The east route has a length of 1150 km including natural river courses and multi-stage pumping stations thus the operation expense is high. For such huge inter-basin water transfer projects with complex conditions of operation, it is necessary to apply automatic canal operations, which can improve the operation of the canal system, insure water transfer security, improve water division efficiency, supply adequate

[1]Professor; School of Water Resources and Hydropower, Wuhan University, Wuhan 430072, China; cdwwh@tom.com
[2]Ph.D graduate; School of Water Resources and Hydropower, Wuhan University, Wuhan 430072, China; yaowhu@163.com
[3]Engineer; Design Institute, Changjiang Water Resources Commission, Wuhan 430010, China; fj66@sohu.com
[4]Lecturer; School of Water Resources and Hydropower, Wuhan University; Wuhan 430072, China; GGH@whu.edu.cn

amounts of water at the right time, avoid water insufficiency and waste, and reduce the costs of operation and management. Now the middle and east routes of the South-to-North water diversion project are in the design stage and parts of the project are underway. Thus, it is urgent and vital to do research works on the operation of long distance water transfer canal systems.

METHOD OF OPERATION AND STORAGE ANALYSES

An effective canal automatic control system must choose an appropriate operation method according to the hydraulic characteristics and targets of its own. The method of operation directly affects the canal regulation storage of water and has a great influence to the canal operation stability. The basic methods of operation are constant downstream depth, constant upstream depth, constant volume, and controlled volume operation method which are identified based on the location of the canal pool water surface pivot point at which the depth remains constant while the water surface slope varies (Buyalski et al. 1991). Since the canal banks of constant upstream depth method of operation must be horizontal to accommodate the zero-flow profile, the construction costs is too expensive for a long distance water transfer canal system. Since it needs to use supervisory control system and design complex software according to the special system circumstances, the implementation of controlled volume operation method is more difficult. Therefore, the methods of constant downstream depth and constant volume operation are chosen to be further studied in this paper.

Constant Downstream Depth

For the constant downstream depth method of operation (see Figure 1), where the water depth at the downstream end of each canal pool remains relatively constant, the canal can be conventionally sized to fit the design flow. The canal freeboard can be minimized, thus reducing the construction costs. However, a canal designed in this manner reacts slowly to the changes of downstream water demand (Wang Changde 1997). Flow changes originating from the downstream end must be relatively small and gradual to avoid excessive fluctuation of water depth.

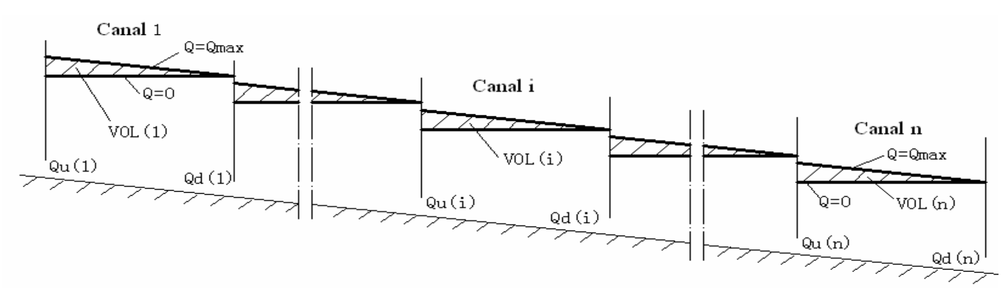


Figure 1. Constant Downstream Depth Method of Canal System Operation

Suppose that the steady state water surface profile is a straight line when the flow rate Q turns from zero to Qmax. It is easy to figure out that the storage of the whole canal system increases, which can be described as $\sum_{i=1}^{n} VOL(i)$. Otherwise, when the flow rate turns from Qmax to zero, the whole storage decreases, which canals be described as $\sum_{i=1}^{n} VOL(i)$. These storage changes originate from the difference between upstream inflow and downstream outflow without considering the turnouts at the canal-side. For a long distance water transfer canal system, the amount of storage change is considerably great, which affects the response and stability performance of the canal system. When an increase from the downstream end of the canal system occurs, inflow change at the upstream end must overcompensate for the outflow in order to accomplish the required volume changes. Inflow must be changed by a greater amount than outflow until the new steady-state profile is achieved. This makes the response to the downstream water demand slow and the transient processes long. The same problem will exist with an outflow decrease.

Constant Volume

The constant volume method of operation is also called "simultaneous operation" because the simultaneous gate operating technique often is used to keep the pool volume constant. The pivot point is located at the middle of the water surface profile for this method (see Figure 2). A relatively constant volume in each pool is maintained by pivoting the water surface about a point near mid-pool as the flow changes from one steady state condition to another, the pool volume can keep relatively balanced by itself. The main advantage of this method is the ability to quickly match different flow rate between supply and demand in the entire canal system, meanwhile, avoiding water shortage or water surplus. The disadvantage of the constant method of operation is the additional canal bank and lining required at the downstream end of each canal pool. However, the additional height required is only about one-half that required for constant upstream depth operation.

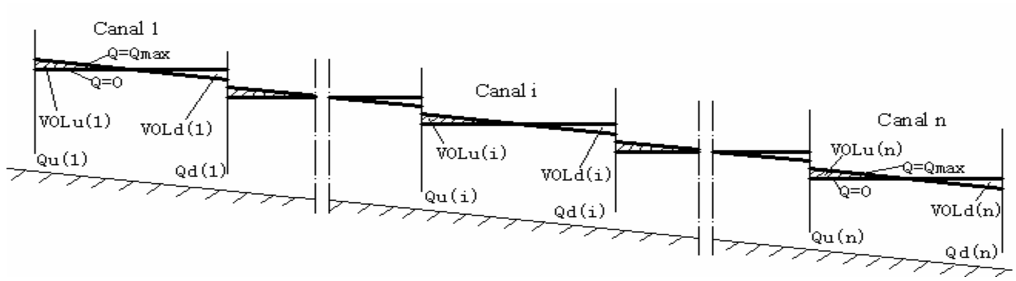


Figure 2. Constant Volume Method of Canal System Operation

Suppose that the steady state water surface profile is a straight line and that when the flow rate Q turns from zero to Qmax, the water storage should increase by $+\sum_{i=1}^{n} VOL_u(i)$ in the upstream half-parts of the pools and decrease by $-\sum_{i=1}^{n} VOL_d(i)$ in the downstream half-parts. The whole volume change can then be expressed as $VOL = \sum_{i=1}^{n} VOL_u(i) - \sum_{i=1}^{n} VOL_d(i) \approx 0$. So the amount of storage change in different flow conditions is not closely associated with the number of pools in series and the time for storage adjustment is almost the same with single pool.

SIMULATION MODEL OF CANAL SYSTEM OPERATIONS

Mathematical Model of Canal System

Usually the main canal is divided into canal pools by check gates in series which contain some turnouts. The check gates upstream and downstream are the boundaries of the conjoint pools. The water transfer canal system showed in figure.3 is composed of n canal pools and there is a huge reservoir upstream as water source. So the upstream boundary condition can be assumed as constant water depth before the headwork check gate. The downstream boundary condition can be discharge or water level with different changing process.

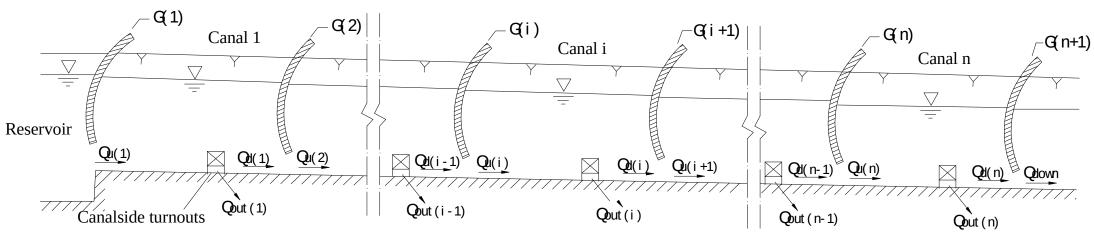


Figure 3. Schematic Diagram of a Typical Canal System

$G(1), G(2) \ldots G(n-1), G(n)$ and $G(n+1)$ represent $n+1$ check gates in the whole canal system. The available water can be conveyed from the canal headwork to downstream turnouts by regulating these gates. $Q_u(i), Q_d(i)$ are the flow rates upstream and downstream of pool i which are the upstream and downstream boundary conditions in the unsteady-flow state. $Q_{out}(i)$ is the flow rate of the turnout accordingly. At the end of each pool, the flow should satisfy a continuous condition, which can be described by:

$$Q_d(i) = Q_u(i) - Q_{out}(i) \tag{1}$$

Because the shape of most canals is a regular prism and the canal cross sections often have little change or keep uniform in one canal pool, we use the Saint-Venant equations to describe the one-dimensional unsteady non-uniform flow in open channel (Xu Zhengfan 1986):

1) Continuity equation

$$B\frac{\partial z}{\partial t}+\frac{\partial Q}{\partial s}=q \tag{2}$$

2) Momentum equation

$$\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{2Q}{gA^2}\frac{\partial Q}{\partial s}+(1-\frac{BQ^2}{gA^3})\frac{\partial z}{\partial s}=\frac{q}{gA}(v_{qs}-v)+\frac{BQ^2}{gA^3}(i+M)-\frac{Q^2}{A^2C^2R} \tag{3}$$

Where B is the width of canal water surface (m); z is the water surface elevation (m); t is the time (s); Q is the discharge (m^3/s); C is the Chezy roughness coefficient; s is the distance along the canal (m); q is the inflow along the canal side (m^3/s/m); g is the gravitational acceleration (m/s^2); A is the cross-sectional area (m^2); v is the flow velocity along the canal axis (m/s); R is the hydraulics radius (m); v_{qs} is the average flow velocity along canal axes of the canal side inflow (m/s), which is usually ignored; i is the canal bottom slope (m/m); and

$M=\frac{1}{B}\frac{\partial A}{\partial s}\Big|_h$. For a prism-shaped canal, M =0 or $\frac{\partial A}{\partial s}\Big|_h$ =0.

The Preissmann implicit scheme is widely adopted as the numerical solution method of Saint-Venant equations for its fine characteristics such as high accuracy and unconditional convergence (Fubo et al. 1994). In this method, the s-t plane of solution domain is divided into regular rectangular net. Then using the difference quotients to approach the partial derivatives of dependent variables (Z and Q), we can deduce the following discrete equations on each grid.

$$a_{1i}Z_i^{j+1}-c_{1i}Q_i^{j+1}+a_{1i}Z_{i+1}^{j+1}+c_{1i}Q_{i+1}^{j+1}=e_{1i} \tag{4}$$

$$a_{2i}Z_i^{j+1}+c_{2i}Q_i^{j+1}-a_{2i}Z_{i+1}^{j+1}+d_{2i}Q_{i+1}^{j+1}=e_{2i} \tag{5}$$

Where $a_{1i}=1$; $c_{1i}=2\theta\frac{\Delta t}{\Delta s_i}\frac{1}{B_M}$; $e_{1i}=Z_i^j+Z_{i+1}^j+\frac{1-\theta}{\theta}c_{1i}(Q_i^j-Q_{i+1}^j)$;

$a_{2i}=2\theta\frac{\Delta t}{\Delta s_i}(V_M{}^2B_M-gA_M)$; $c_{2i}=1-4\theta\frac{\Delta t}{\Delta s_i}V_M$; $d_{2i}=1+4\theta\frac{\Delta t}{\Delta s_i}V_M$;

$$e_{2i}=\frac{1-\theta}{\theta}a_{2i}(Z_{i+1}^j-Z_i^j)+[1-4(1-\theta)\frac{\Delta t}{\Delta s_i}V_M]Q_{i+1}^j+[1+4(1-\theta)\frac{\Delta t}{\Delta s_i}V_M]Q_i^j$$

$$+2\Delta tV_M{}^2\frac{A_{i+1}(Z_M)-A_i(Z_M)}{\Delta s_i}-2\Delta t\frac{gn^2Q_M{}^2P_M{}^{4/3}}{A_M{}^{7/3}}\text{。}$$

Where the hydraulics parameter of the difference center $\varphi_M=\theta(\frac{\varphi_i^{j+1}+\varphi_{i+1}^{j+1}}{2})+(1-\theta)\frac{\varphi_i^j+\varphi_{i+1}^j}{2}$ φ generally refers to the water surface elevation Z, the discharge Q, the velocity V, the water surface width B, the cross-sectional area A or the wetted perimeter P; The subscript i is the space layer serial number, the superscript j is the time layer serial number, θ is the

weight factor (usually choose from 0.7~0.75).
One grid of the net represents one computational canal segment and one canal segment can deduce two equations above. For a canal divided by N cross sections which has N-1 canal segments, 2N-2 equations can be established. By adding equations for the upstream and downstream boundary conditions of each canal pool, we can get 2N equations for 2N variables. Combining all the 2N equations, we can get large-scale sparse nonlinear equations which can be solved by double elimination method (recursion method).

Simulation Model of Canal System Operation

The automatic control of canal system realizes the scheduled control targets by adjusting the control equipment such as the check gate according to the required pool water level and flow along the canal. Both the hydraulic characteristics and the application of control theory associated should be considered. The simulation program of long distance water transfer canal system including siphons, aqueducts and turnouts was constituted. For the discharge feed-forward plus water level feedback controller, the frame of the control system is shown in Figure 4.

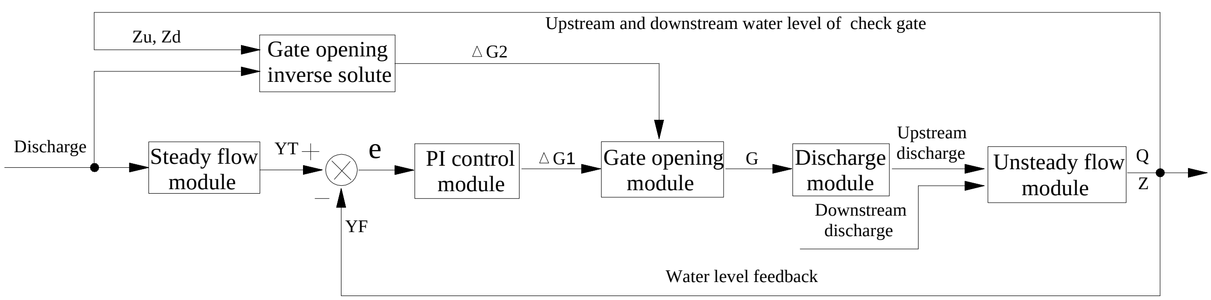


Figure 4. Canal Automation Control Systems

The entire canal automation simulation system is composed by six modules: the steady flow calculation module, the gate opening inverse-solute module, the PI control module, the calculation module for gate opening, the calculation module for the discharge through the gate and the unsteady flow calculation module (see Figure 4), these six modules are closely tied and act mutually to realize the operation target together. Accordingly, there are four core subroutines connected by the main program of simulation, the functions and algorithms of which can be detailed as follows.

Steady-State Flow Calculation Subroutine. This subroutine is used for calculating the water surface profile of canal pools in different steady-state conditions. The calculation formula based on energy method can be described by:

$$\Delta E_s = (i - \overline{J})\Delta s_{1-2} \tag{6}$$

Where ΔE_s is the energy difference of two continuous calculating sections， $E_s = h + \frac{\alpha v^2}{2g}$; i is the canal bottom slope; $\overline{J}$ is the average hydraulic gradient between two continuous calculating sections; Δs is the distance of two continuous calculating sections.

Steady-state flow calculation subroutine has two functions for the main program: calculating water surface profile before flow changes occur to provide initial conditions for unsteady flow calculation and calculating the target water surface profile when flow state changes (turnout and downstream water demand). For the constant volume method of operation, the main program calls it to calculate the target water surface profile on the condition of aim volume. For the constant downstream depth method of operation, the main program calls it to calculate the target water surface profile on the condition of constant downstream depth. The upstream end and downstream end of the target water surface profile can be used as water level controlled points of the canal operation system.

Unsteady Flow Calculation Subroutine. The Saint-Venant equations were used to describe one-dimensional unsteady non-uniform flow in open channel. The numerical solutions in the subroutine include characteristics method, explicit difference method and implicit difference method. By comparison among these methods, we found that the characteristics method introduces much calculation error, moreover, it even cause non-conservation of discharge for large canal system. While Preissmann implicit method whose discrete equations are presented above can reach convergence in any condition and there is no close error.

Control Algorithm Subroutine. Control algorithm is the core of the control of canals which processes the input information and calculates the proper output to the actuator. Generally, the control algorithms include: Three point control, EL-FLO and EL-FLO+ Reset control, P+PR control, intelligent control, model predictive control, etc.(Rogers and Goussard 1998; Malatterre et al. 1998). The logics of control mainly include: feedback, feed-forward and compound control (feedback + feed-forward). For a complex multivariable system, it is better to take compound control such as discharge feed-forward control plus water level feedback PI control according to our study. The incremental PI control algorithm can be described as follow:

$$\Delta G(k) = K_P\left[e(k) - e(k-1)\right] + K_I e(k) = K_P \Delta e(k) + K_I e(k) \tag{7}$$

Where ΔG is the output of feed-back control; K_P is the proportional coefficient; K_I is the integral coefficient; e is the difference of water levels; Δe is described by $\Delta e(k) = e(k) - e(k-1)$; k is the sampling time.

Usually, the inputs of controller are the difference of water levels and its difference ratio of the single canal pool at a time. In other words, the gate increment ΔG_i is only based on the difference e_i of single canal pool which can be described as $\Delta G_i = f(e_i)$. But the flow information from all downstream canal pools will influence the upstream flow state according to downstream control concept. So we use difference information from all downstream canal pools as the input of the controller to produce upstream gate increment which can be described as:

$$\Delta G_i = f(\sum_{j=i}^{n} e_j) \tag{8}$$

Discharge Calculation Subroutine. We use the gate discharge formula including velocity head to calculate the flow rate through a gate which can be described as follow:

$$Q = C_d ab\sqrt{2g\Delta H + (Q/A_u)^2} \tag{9}$$

Where Q is the discharge through the gate (m^3/s); C_d is the discharge coefficient; a is the gate opening (m); b is the gate width (m); ΔH is the difference between upstream water depth H_u and downstream water depth H_d (m); A_u is the cross-sectional area before the gate (m^2). Discharge calculation module contains two parts which can be described by two functions, $Q = f(a,b,Hu,Hd)$ and $a = f^{-1}(Q,b,Hu,Hd)$, the first one is used to calculate flow rate through the gate as the boundary condition for unsteady flow calculation, the second one is used to reversely deduce the gate opening in feed-forward control.

Special Treatments to Structures

Aqueducts, tunnels and closed conduits, such structures with free water surface can be regarded as special sections of canals. We just enhance mesh density of the s-t plane of solution domain to improve the calculation accuracy.

The flow inside inverted siphons with pressure can not be described by Saint-Venant equations. The discharge through the inverted siphon can be calculated by the formulas as follow:

$$Q = \mu\omega\sqrt{2gz} \tag{10}$$

$$z = h_f + h_j = (\zeta_f + \Sigma\zeta_j)\frac{v^2}{2g} \tag{11}$$

$$\mu = \frac{1}{\sqrt{\zeta_f + \Sigma\zeta_j}} = \frac{1}{\sqrt{\lambda\dfrac{L}{D_B} + \Sigma\zeta_j}} \tag{12}$$

$$\lambda = 8g/C^2 = 8gn^2/R^{1/3} \tag{13}$$

Where Q is the discharge in the inverted siphon (m^3/s); ω is the cross-sectional area (m^2); z is the water head difference between entrance and exit (m); μ is the discharge coefficient; ζ_f is the coefficient of friction loss of head; $\sum\zeta_j$ is the sum of local head loss coefficients; L is the length of inverted siphon (m); D_B is the inner diameter of pipe (m); h_f is the friction loss of head(m); h_j is the local head loss (m); v is the average flow velocity in siphon; R is the hydraulics radius (m); n is the manning roughness coefficient; g is the gravitational acceleration (m/s^2). Approximately, the relation between Q and $\sqrt{z}$ can be simplified as $Q = K\sqrt{z}$, K is the coefficient which can be gained from design condition.

$$K = \frac{Q_{des}}{\sqrt{z_{des}}} \tag{14}$$

Where Q_{des} is the discharge and z_{des} is the water head difference in design condition. In simulating the inverted siphons, we are only concerned with the relations of water level and discharge at the starting point and the ending point, while ignoring the water movement inside the siphon (Liu Shupiao et al. 2001).

EXAMPLE OF SIMULATION AND RESULTS

Simulation Case

The emergency sector is the last part of the middle route of South-to-North water diversion project, which starts at Guyun check gate, ends at a place near Beijing. The canal sector runs through Hebei province whose total length is 127.298km (Zhang Zhiming and Wen Dan 1997). The whole canal system is divided into 13 canal pools by check gates, including 12 turnouts, 16 inverted siphons, 3 aqueducts, and many tunnels, bridges, and drainage structures. The designed inflow rate is 170m^3/s at the beginning and 60m^3/s at the end. The general parameters are presented at Table 1. The pools are farther divided into small parts according to the basis as follow:

a. The changes of canal parameters (manning roughness coefficient n ; bottom slope i ; bottom width b ; side-slop m). The boundary of sub-division of canal pool is the place where the canal parameters changes to ensure that every sub-divisions have the same parameters.

b. The location of turnout. It is a boundary of sub-division of canal pool because the flow rate changes abruptly at these places where the water level and flow rate of the pool should meet continuous boundary conditions.

c. The location of inverted siphons. The inverted siphons can not be described by Saint-Venant equations because the flows through the siphons are pressure flows. We simplify the siphon as a cross-section at a pool which is the boundary of the sub-divisions.

d. The transition of pools. Canal and structure are usually linked by pool transition, we divide the transition of pools into several parts to improve the accuracy of calculation.

e. Some parts need to enhance mesh density. The flows of the tunnels with no pressure and the aqueducts can be described by Saint-Venant equations, but the length is relatively short, so we densify the calculation nets by taking these structures as single sub-divisions to improve the simulation accuracy.

Table 1. General Parameters of Canals

Canal No.	Sub-division number	Length (m)	Design water depth (m)	Design flow rate (m^3/s)	Bottom altitude (m)	
					Upstream	Downstream
1	5	9759	6.00	170	70.253	70.141
2	4	22053	5.00	170	69.991	69.032
3	4	15177	5.00	165	68.882	67.728
4	6	19553	5.00	155	67.578	66.475
5	3	9234	5.00	135	66.325	66.139
6	5	25697	4.50	135	65.989	64.935
7	3	13198	4.50	135	64.812	64.295
8	7	27098	4.50	135	64.145	61.486
9	4	9717	4.50	125	61.336	60.771
10	2	14924	4.50	100	60.621	59.920
11	5	20829	4.30	60	59.770	58.695
12	4	14705	4.30	60	58.545	57.849
13	8	25314	4.30	60	57.699	56.500

Note: drop at each gate 0.15m.

Suppose that the canal system is fed by a constant-level reservoir whose water level is 7.0 m. To simplify the simulation, we concern only Zhongguan turnout (in fourth pool) and Tianjin main canal intake (in ninth pool) with a scheduled flow rate changing process showed in figure 5 and the downstream flow rate of the canal system also changes, other turnouts keep zero flow rate.

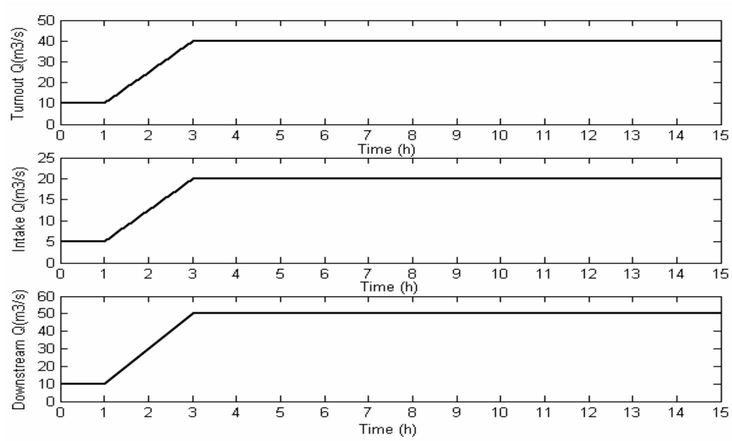


Figure 5. Diversion Discharge Changing Process

Simulation Results

The simulation results about the real-time water levels changing process are showed in Figure 10 and Figure 11. The changing processes of water level errors between real-time water levels and target water levels are showed in Figure 8 and Figure 9. The gate opening changing processes are showed in Figure 6 and Figure 7.

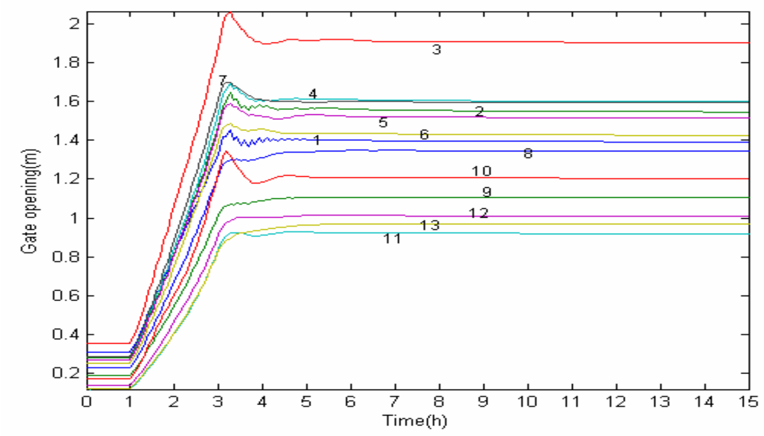


Figure 6. Gate Opening in Dynamic Process (Constant Volume)

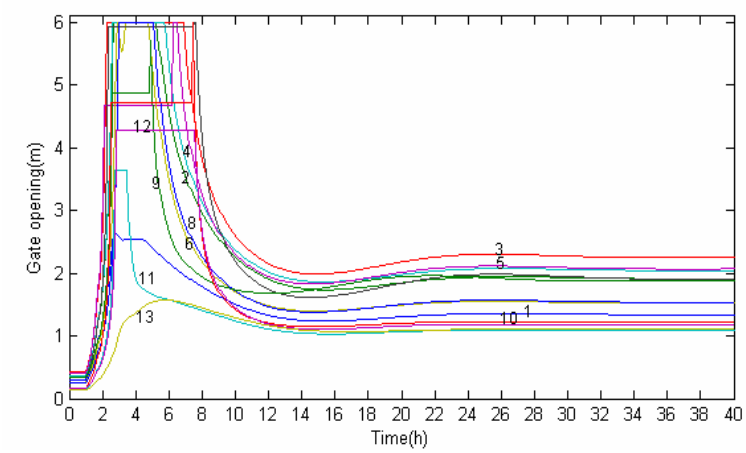


Figure 7. Gate Opening in Dynamic Process (Constant Downstream Depth)

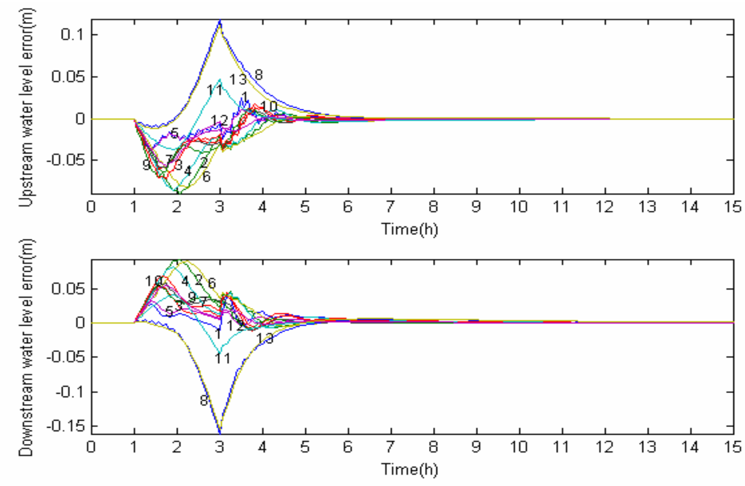


Figure 8. Water Level Error in Dynamic Process (Constant Volume)

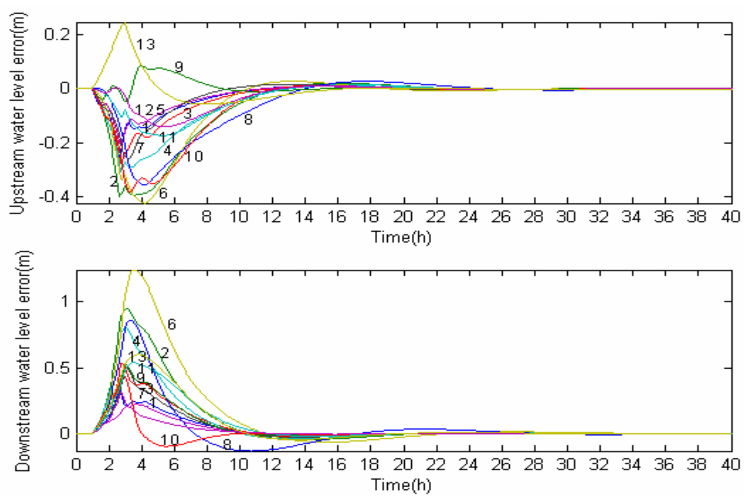


Figure 9. Water Level Error in Dynamic Process (Constant Downstream Depth)

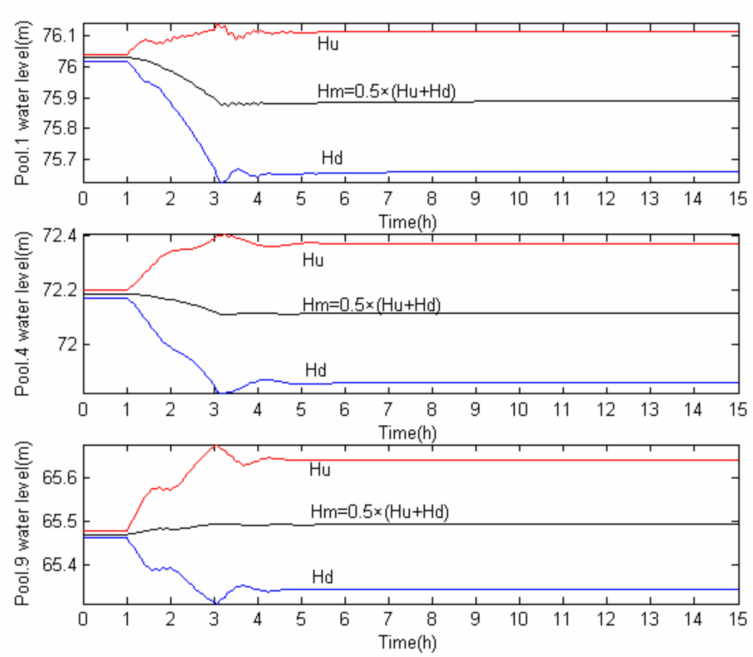


Figure 10. Water Level in Dynamic Process (Constant Volume)

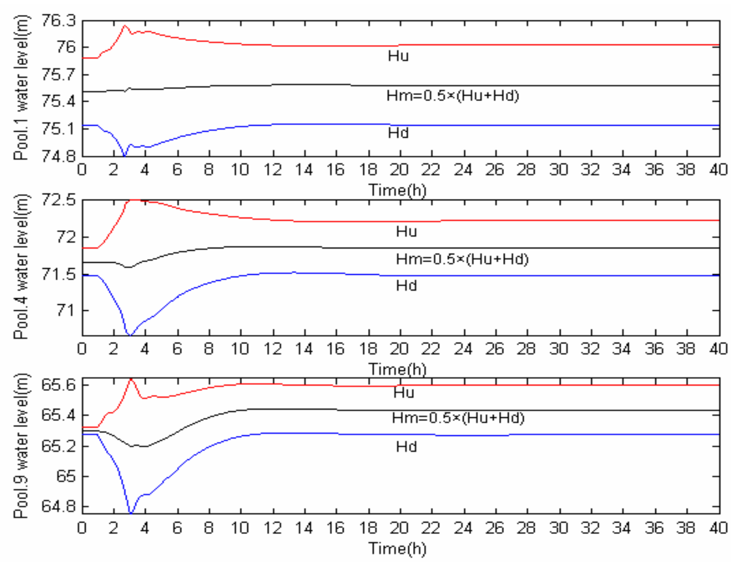


Figure 11. Water Level in Dynamic Process (Constant Downstream Depth)

From the simulation results, some representative indicators for performance comparison of the two methods of operation are shown in Table 2.

Table 2. Performance Indicators

Method of operation	Max stable time of gate (h)	Max over-shoot of gate (m)	Max stable time of water level (h)	Max water lever error (m)
Constant volume	4	0.18	4	0.16
Constant downstream	22	Max opening	20	1.25

Note: water level error means the difference between real-time water level and target water level

CONCLUSIONS

This paper analyses the characteristics of water storage adjustment under two different methods of operation and presents a simulation model of long distance water transfer canal system including siphons, aqueducts and turnouts. The simulation results of the emergency sector of middle route of South-to-North water diversion project as a typical case show that the operation performance of constant volume control method is better than the operation performance of constant downstream water depth control. From above, several conclusions can be drawn:

(1) In the same condition, the constant volume method is more suitable than the constant downstream depth method for the long distance water transfer projects, especially for systems which lack in-line storage. The constant volume method is more suitable because in constant downstream depth method, the storage change of each pool should be supplied by the headwork (when flow rate increase) or consumed by the downstream pool (when flow rate decrease). Therefore, the whole canal system can’t get a quick response and the stabilization time turns to be long.

(2) To achieve stable water surface profiles, taking the upper and end point of the pool as control points is reasonable and effective. The proper choice of feedback, feed-forward, and compound method can make the control more effective.

(3) Generally, the pool nearest to the water intake is the first one to restore stability in dynamic process of canal system. The further the pool is away from the head, the longer time it will be. But take the sum of all the downstream differences between real-time and target information as the input of the controller is of great benefit to eliminate time lag.

REFERENCES

Burt, C. M.. (1987). “Overview of Canal Control Concepts.” Planning, Operation, Rehabilitation, and Automation of Irrigation Water Delivery System, ASCE, New York.

C.P.Buyalski, D.G.Ehler, H.T.Falvey, D.C.Rogers, E.A.Serfozo. (1991). Canal Systems Automation Manual, Vol.1, U.S. Bureau of Reclamation, Denver, Colo.

Wang Changde, and Zhang Liwei. (1997). “Mathematical model of dynamic process of hydraulic automatically operated canals with Constant downstream level controller.” Journal of Hydraulic engineering, 11:11-19.

Xu Zhengfan. (1986). Hydraulics, Higher education press, Beijing.

Fubo Liu, Jan Feyen, Jean Berlamont. (1994). “Downstream Control Algorithm for Irrigation Canals.” Journal of Irrigation and Drainage Engineering, 3:468-483.

Rogers, D.C. and Goussard, J. (1998). “Canal Control Algorithms Currently in Use.” Journal of Irrigation and Drainage Engineering, 1:11-15.

Malaterre, P.O., Rogers, D.C., and Schuurmans, J. (1998). “Classification of Canal Control Algorithms.” Journal of Irrigation and drainage engineering, 1:2-5.

Liu Shupiao, Wang Changde, Cui Yuyan. (2001). “P+PR algorithm control for multireach canal systems with inverted siphons in series.” China Rural Water and Hydropower, 10:30-32.

Zhang Zhiming, and Wen Dan. (1997). The general layout of main canals of South-to-North water diversion project. Changjiang Water Resources Commission, Wuhan.

A PRACTICAL METHOD FOR VOLUMETRIC DELIVERY OF WATER

Ahmad Pourzand[1]

ABSTRACT

Volumetric delivery of water in irrigation networks has been recognized as a major step for optimum use of water for agricultural purposes. This requires an appropriate water demand management, associated equipment, and an information system. In this paper, a summary of a guideline for volumetric water delivery in irrigation networks of Iran has been presented. In this regard, the principles and prerequisite conditions for volumetric water delivery have been discussed. Also the processes of signing an agreement with the water users and details of water delivery have been defined. Furthermore topics of training for different stakeholders in the irrigation network including managers, water distributors, and representatives of the farmers have been introduced.

INTRODUCTION

Water scarcity and the need for more agricultural products requires paying close attention to optimum use of water for agriculture. In this regard, the high loss of water, especially in the case of surface water usage, is a fact which should be seriously considered.

Volumetric delivery of water for irrigation is the first step for controlling water demand for agricultural purposes and reduction of water loss for this type of demands. Most of the irrigation networks in Iran are equipped with water level regulators and gates capable of volumetric delivery to the water users. However, actual water allocation and fees are based on the cultivated area and not on the volume of water consumption by the farmers. That is the main reason that the accuracy of the volumetric delivery system is not high. Furthermore, since water users do not pay on a volumetric basis of consumed water, they do not care much about reduction of water uses.

To address the above mentioned issues, the current status of water delivery in selected irrigation networks of Iran was first investigated. It has then been tried to propose practical ways to improve the current situation by advising application of appropriate technology and equipments for volumetric water distribution in these irrigation networks.

The finding of this study showed that for volumetric delivery of water in irrigation networks as well as charging farmers on the basis of volume of water consumed for production of agricultural goods, it is necessary to provide the three following conditions:

- Principles and conditions which should be prepared and agreed on for volumetric water delivery.

[1] Manager of Section for Operation and Maintenance, Department of Irrigation and Drainage, Mahab Ghodds Consulting Engineering Company, No. 17, Takherstan Alley, Vahid Dastgerdai Avenue, Tehran, Iran; a_pourzand@yahoo.com

- Processes for signing an agreement with the water users and details of water delivery should be defined.

- Training topics for different stakeholders in the irrigation network including managers, water distributors, and representatives of the farmers should be introduced.

PREREQUISITE CONDITIONS

To deliver water in an irrigation network on a volumetric basis, certain principles and conditions in water management, information database and application of reports must be met. The system for regulation, delivery and measurement of water in the irrigation network should also have minimum requirements for this purpose. In this paper, it is mostly assumed that an upstream control system is used for the open canal irrigation network. The above-mentioned principles are discussed below.

Water Distribution Management

Volume of Water as the Basis for Water Delivery and Fees. Water should be delivered on the volumetric basis and the water fees should be calculated and charged accordingly.

Role of Users' Demand in Water Delivery. Each water delivery for certain days should be carried out upon request of the users (or their representatives). Therefore, water distribution according to a schedule with pre-specified rotations, in which water would necessarily be delivered to their representatives, will not be possible in this system. If water users are going to pay for the volume of delivered water, they themselves should request it. The water distribution institutions, however, can match the requests with the situation and change the quantity and timing of the requests according to monthly quota, subject to the users' agreement.

Unit of Delivered Water Volume. In this system, unit volume for water is liters per day (24 hours). For instance, 50 liters per second for 24 hours would be equivalent to 4320CM.

Point of Water Delivery to Users. Selection of delivery point is vital in the volumetric system of water delivery. Considering the capacity of each water delivery gate and the need to regulate(variation) them once per day, the delivery point should be selected such that the minimum required time for users of that irrigation rotation would not be less than 24 hours. The larger an area which a delivery point covers, the higher would be the water demand and the longer period of delivery. If the irrigation rotation is less than 24 hours, it would be necessary to regulate gates in three working periods per day which would be an expensive and complicated job. The water, received by the users, will be distributed to the farms in multi hour rotations which is a responsibility of the water users' representatives.

Water Users' Association. For volumetric delivery of water, it is necessary to have organized users downstream of each delivery point. It is preferred that such organizations be formal or somehow registered in legal forms such as cooperatives, associations, and stock companies. However, a simple way for this purpose could be that users downstream of each delivery point elect one representative or waterman among themselves, even if a formal association does not exist. In this case, the total volume of water for the users, requested by their representatives, must be sufficient for irrigation in multiple days (i.e., 1, 2, … day).

Allocation of Water to Users. The required water for farms, supplied by an irrigation network, should somehow be determined (e.g., project study reports, agreements, etc.) and reported to the users. This amount of water will be calculated according to cropping pattern, crop water requirement and accepted efficiency figure for the cultivated area supplied by each off take (or representative of farmers) for each irrigation season.

Table 1 depicts required water for different crops per year. In each cell of this table, required water for different type of crops for each month of a year will be written. The sum of these amounts for all of the mentioned type of crops will be written in the row entitled Total. Assuming that a portion of required water can be supplied from other sources (e.g., water wells, springs, …), the remaining amount, which has to be supplied by the irrigation network, will be written in the next row for each month. The mentioned rows are only applicable to those networks which use surface and ground water conjunctively.

Table 1. Required Water for Different Crops per Year (CM)

Month of irrigation season / Type of Crops-ha	1	2	3	4	5	6	7	8	9	10	11	12	Comments
Crop 1													
Crop 2													
Crop 3													
Crop 4													
Crop . . .													
Total													
Reduce: supplied water from other sources													
Allocated water from irrigation network													

Signing Agreement with Water Users. In the volumetric system of water delivery, it is very important to sign an agreement with the water users/representatives. Table 1 should be used in the text of the agreement. Also, the code or number of the gate and name or names of representatives of the users who can request for water should be mentioned in the agreement. As mentioned before, this would serve as the basis for trading of the volume of water in the amount and distribution over the operation period as defined by Table 1.

One important point which should be mentioned in the agreement for volumetric water delivery is that the amount of water mentioned in Table 1 is a predicted value and the actual delivery of those are subject to water availability. For any un-foreseen condition such as drought, the volume of delivered water will be less than the predicted values in Table 1.

Calculation of Water Fees. The charges for water should be transformed to volumetric-based fees according to current laws and regulations. Fees, calculated in this way, have a fixed value for an irrigation network or a district which has a cropping pattern similar to those in the agreement.

No Need for Measurement of Cultivation Area in the Volumetric Delivery System. On the basis of cropping pattern and the gross required water, certain amount of water will be delivered to the user and fees would be charged according to the volume of water requested by the user. In this system, it is the user who decides what combination of cropping pattern he should select which would have the maximum benefit for the available amount of water which he has paid for. On the other hand, the water distribution organization does not need to survey the cropping pattern and water usage. In this way, the organization would not face difficulties in water distribution. Since the volume of delivered water is limited to the required water for the cropping pattern, the users automatically will be inclined to select a combination of cropping close to the defined cropping pattern. Therefore, in the volumetric system of water delivery, measurement of cultivation area will not be carried out with the objective of calculation of water fees.

Collection of Water Fees. water fees can be collected by cash or credit. For the cash sale, water fees are transferred by the users/representatives to the specified account at the time of approval of the request and water will be delivered to the user according to the distribution schedule. It is also possible to calculate the total amount of delivered water at the end of each irrigation season and collect fees accordingly. Alternatively, users can pay some deposit and after delivery of water the fees can be deducted from the credit. If any of these payment methods are going to be applied, they should be mentioned in the agreement with the users.

Inclusion of Water Loss. Considering that water fees will be calculated on the basis of volumetric water delivery, it is important that the agreed amount of water actually be delivered. In this regard, water losses in the transmission system terminating to the delivery point should always be considered. Therefore, the inflow of the network including the losses should be higher than the sum of amounts which should be delivered to the users. In other words, the operating organization is responsible for the volume of water loss in the system.

Equipment for Water Delivery

In the volumetric system of water delivery in irrigation networks, required equipment for delivery plays a major role. If the users are going to pay for each cubic meter of water, the equipment for water delivery should be sensitive enough for this purpose. For volumetric delivery the equipment should not only show amount of discharge at the off take but also be capable of controlling the flow rate according to the request of users. Therefore, the networks which are based on the volumetric system of water delivery and pricing should be equipped with accurate water delivery systems.

Automatic System of Water Level Regulation at Offtakes. It is necessary to have automatic water level regulators at the offtakes so that the water level would remain relatively constant at these locations. Therefore, application of automatic systems for water level regulation at offtakes is vital.

Water Measurement and Delivery System. Two types of gates are used in these systems. Modular gates are the best for volumetric water delivery. The gates are capable of water delivery with an accuracy of more than 90%, even if water levels slightly vary at the offtakes. It is of course necessary to regulate water level at the intakes.

Slide and radial gates. Slide and radial gates are used for volumetric water delivery in those tertiary networks with no modular gates but with automatic regulators. The required water discharge could be delivered by adjusting the gate openings in relation to requested water, assuming that the water level at the offtakes is constant. In these cases, water discharge can be measured by a Parshall flume, weir, or a calibrated gauge at certain stations.

Application of Information for Volumetric Water Delivery

In the volumetric system of water delivery, access to timely information is very important. Considering the role of water user's demand in the process of water distribution, it is necessary to have time and accurate information of the daily demand of network canals. Such as number of water requirements that have to be met in each day, regulation of canals flows based on the water requirements and the off take supplying water and the ones without water in a specific day.

Therefore, the following information is required for volumetric water delivery.

Full Information of Water Users. Name of representative or representatives and their subscription number, land and cultivated area, type of crops, name of village, assigned canal and delivery points, water demand according to Table 1, date and reference number of the agreement, etc.

Water Demand Information. This includes: the requested discharge in terms of liters per second, date of start and period of each water delivery in terms of days, the location of water delivery point, name of the representative requesting water and the person who receives it.

Daily Schedule of Water Distribution. This is required at gate locations of the main canal, primary canal, secondary canal and the water supply point.

PROCESS OF VOLUMERTIC DELIVERY OF WATER

As shown in Figures 1 and 2, the process of volumetric delivery of water includes the following components:

Process of Signing Agreement with Water Users

Introducing the Representative of Water Users for each Delivery Point. The first step for volumetric delivery of water is to introduce a representative for users downstream of each delivery point. Users can also introduce one representative for more than one offtake. It is advantageous that the representative would be introduced upon co-ordination and approval of the local agricultural unit. Otherwise, all of the users can select their representative and introduce him to the operation organization in writing.

Providing Cultivation Schedule and Required Water. Following introduction of the representative/s, the cultivation schedule and water demand will be provided by him. At this stage the operation organization checks the requested water with the cropping pattern and the regulations (quota). If there is no controversy, the cultivation schedule and water demand will be passed to the relevant organization for signing an agreement.

Signing Agreement with the Representatives of Water Users. Agreements will be signed with the representatives of water users. It is clearly mentioned in the agreement that water will volumetrically be delivered to the users according to the table included in the agreement upon each request of the representative. Water fees, per cubic meter of delivered water, will then be collected from the users at the approved rate.

In the process of signing agreements, it is important that the water distribution organization keeps a record of its commitments for water supply and delivery to users and makes sure that the total amount of required water for each region will not exceed from the canal conveyance and the maximum amount of deliverable water of the irrigation network. For those networks which are directly fed by rivers and might face some uncertainties in water supply, the forecast will be carried on the basis of minimum river flow for the month with maximum demand per year.

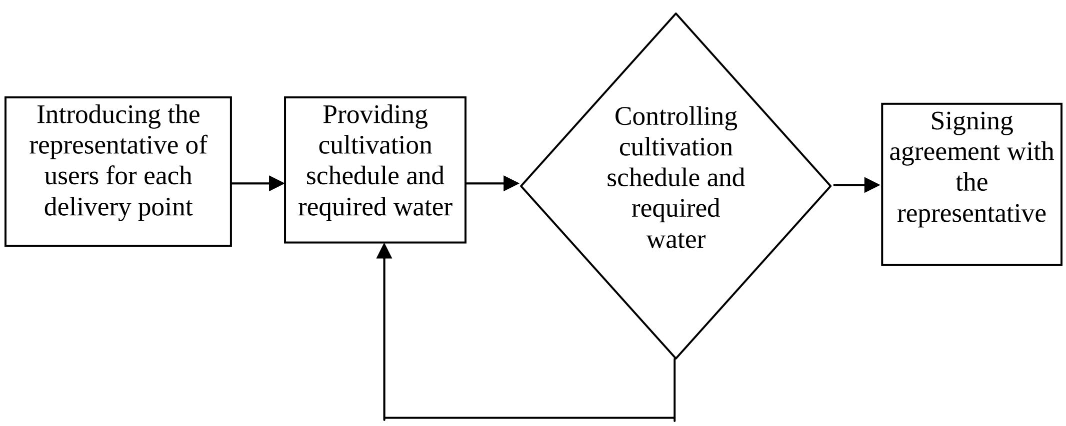


Figure 1. Process of Signing Agreement with Water Users

Process of Water Delivery to the Users

Those users who have signed their agreements are eligible to receive their required amount of water. As shown in Figure 2, the process of water delivery to the users includes the following components:

Request for Water by the Users. For each irrigation rotation, request for specified amount of water (lit/s) and associated duration (days) will be given in writing. In the request information such as name of the representative, reference number of the agreement, intake gate, amount and duration of water and the start date of water delivery will be included. This request will be checked against the irrigation schedule, included in the agreement, and if there is no controversy will be approved. Then, start time and discharge of irrigation will be agreed with the representative and recorded on the request form which will be ready for delivery.

Approval of the Request. Upon approval of the water request by the manager of water sale or any other responsible person in the operation organization, the request will be delivered to the canal responsible person.

Request by the Canal Responsible Person. Considering the total amount of requested water as well as the total amount of requests which their delivery will be finished per day, the responsible person for the canal will request for increase or decrease of discharge in the canals under his management.

Water Discharge Regulation in the Canals: A summary of requests, made by the responsible persons of the canals, will determine the variation of discharge in the main and secondary canals and the managers for the upstream canals will regulate them accordingly.

Water Delivery to Users' Representative: For each offtake, water delivery will be carried out at a certain time of the day. The amount of water, agreed with the canal manager, will be released through gates, measured and delivered in presence of the user's representative. The water release will be terminated at the pre-agreed time.

Recording Possible Water Delivery Variations: Further to submission of requests, the responsible person for the canals will finalize and report any changes in the processes of water delivery.

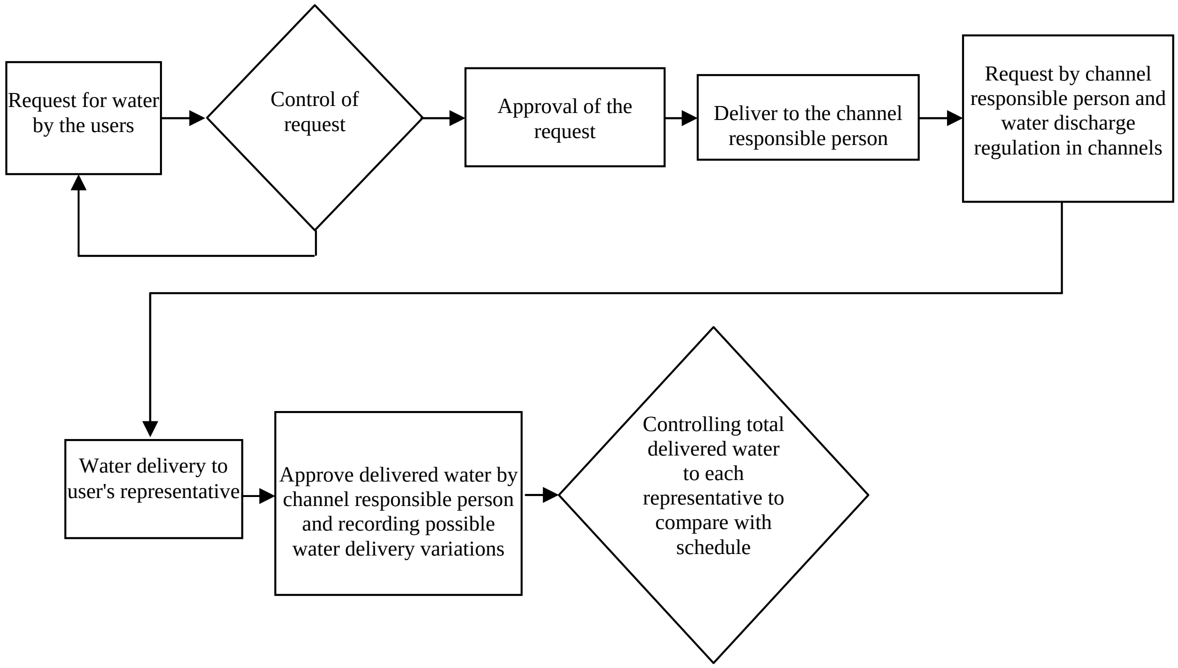


Figure 2. Process of Water Delivery to the Users

TRAININGS FOR VOLUMETRIC WATER DELIEVERY

To deliver water on volumetric basis, required on the job training, should be provided at three levels:

- Training for mangers and responsible persons of the irrigation network
- Training for water delivery operators
- Training for representatives of water users

Training for Managers and Responsible Persons

Training includes the following:

-Introduction to water distribution planning in irrigation networks

- Forecast of yearly water resources supply
- Forecast of yearly demand of irrigation network
- Planning water for distribution in the network per month

-Introduction to water control in the main network

- Network response to variations of inflow and demands
- Performance of equipment for water level regulation, measurement and delivery
- Loss in the main canals of the network
- Comparison of cropping pattern required by the users with the network pattern

- Calculation of monthly need of water users groups on the basis of gross water demand according to agreed pattern
- Methods for mitigation of flood and drought effects
- Method for calculation of water fees per cubic meter of water

-Introduction to database of irrigation network
- Method for collection and generation of data
- Preparation of schedule and tables for water distribution in the canals for the managers
- Application of information for supervision and performance control of water distribution and delivery in the network

-Introduction to laws and regulations for water distribution management

Training for Water Delivery Operators

-Introduction to cropping pattern and water demand table of water users groups

-Introduction to volumetric water delivery and calculation of its daily discharge on the basis of volume of water, specified in the agreement

-Introduction to operation of water delivery and regulation system
- Structure of equipment and their application
- Periodic and daily demand
- Method of regulation and performance monitoring of the installations
- Usual problems of the facilities and their trouble shooting

-Methods of communications and guiding water users/representatives
- Introduction to irrigation rotation in the networks under management of the representatives
- Introduction to laws and regulations for water distribution and delivery
- Introduction to preparation of forms for information and formats of reports
- Methods of interaction with the water users and confidence building

-Introduction to calculation of water loss in the canals

Training for Water Users

-Introduction to collection of users reports for yearly cultivation in accordance with the cropping pattern and water demand

-Introduction to calculation of water demand for crops and converting volumes to daily discharge

-Introduction to water circulation in the area under management of each representative and fair distribution of water among them

-Introduction to water fees and ways of it collection from the users

-Introduction to laws and regulations for water delivery and distribution in the network

-Introduction to water measurement using facilities and equipment in the network under their management, offtakes and daily services and maintenance of such facilities

MAPPING SYSTEM AND SERVICES FOR CANAL OPERATION TECHNIQUES: THE MASSCOTE APPROACH

Daniel Renault[1]
Thierry Facon[2]
Robina Wahaj[3]

ABSTRACT

On the basis of previous tools and approaches widely used in Asia by the Food and Agriculture Organization (FAO) in its modernization program (Rapid Appraisal Procedure (RAP) & Benchmarking), FAO has developed a systematic approach for canal operation improvement from the diagnosis up to the formulation of operational units and planning of a service objective agreed upon with the users.

The proposed comprehensive methodology for analyzing canal operation modernization, is based on a systematic mapping exercise: MApping System and Services for Canal Operation TEchniques – **MASSCOTE** (FAO, 2007). It consists of successively mapping:

- **Performance, through a Rapid Appraisal Procedure (RAP):** to diagnose the processes and assess performance, increase knowledge about the constraints and opportunities which the system management has to consider.
- **System Capacity and Behaviour (Sensitivity) :** to assess the capacity of a canal network with regards to its various function (transport, diversion, control, etc.), as well as its behaviour through the sensitivity analysis.
- **Perturbations:** which describes the disturbances (occurrences, magnitudes) that are likely to occur along the irrigation canal systems
- **Water Networks and Water Balance:** which influence the way water resources circulate, are managed and monitored
- **Service to Users:** to determine service objective characteristics tailored to the user' needs and willingness to pay,
- **Partitioning of Sub-Management Units:** many large systems should be split into small (but not too small) manageable units. In the context of management transfer, users associations should be large enough to be able to recruit a professional to properly operate their sub-system.
- **Demand for Canal Operation**, which depends on the service requirements, the perturbations, the opportunities for water management, and the capacity and sensitivity of the irrigation structures.
- **Options for Canal Operation Improvements,** which are determined by the local conditions, availability of resources and capacity in mastering upgraded techniques

---

[1] Senior Officer Irrigation System Management , Land and Water Development Division (NRLW), FAO Viale delle Terme di Caracalla 00100 Rome ITALY Tel:00 39 06 570 54713 Mobile: 00 39 34 01 61 32 00 e-mail:daniel.renault@fao.org
[2] Senior Officer Water Management, Land and Water Development Division (NRLW),RAP FAO Bangkok e-mail:thierry.facont@fao.org
[3] FAO Consultant Land and Water Development Division (NRLW), FAO Viale delle Terme di Caracalla 00100 Rome ITALY e-mail:robina.wahaj@fao.org

- **Consolidation of a System Management Plan,** with the goal to ensure consistency among the management units at the upper level.

This paper describes the MASSCOTE methodology for developing a strategy for improvements in canal operation and the lessons learned from its application in several countries of Asia.

MASSCOTE: A METHODOLOGY FOR DEVELOPING MODERNIZATION PLANS

A major part of the 250 millions hectares irrigated worldwide is served by surface canal systems. In many cases performance is low to mediocre and improvements are critically needed in (i) water resource management, (ii) service to irrigated agriculture and (iii) cost-effectiveness of infrastructure management.

The Food and Agriculture Organization of the United Nations (FAO), particularly in Asia, has concentrated its efforts in recent years on the promotion of the modernization of irrigation systems.

At a regional consultation in Bangkok, 1996 (FAO, 1997), the following definition was proposed for the modernization of irrigation systems:

> "Irrigation modernization is a process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes with the objective to improve resource utilization (labor, water, economics, environmental) and water delivery service to farms."

As part of this effort FAO has developed and field tested a comprehensive methodology which allows professionals to develop solutions for irrigation management and operation that works and serves the users better. This methodology is named MASSCOTE for MApping System and Services for Canal Operation TEchniques.

Canal operation is at the heart of the MASSCOTE approach for two main reasons:

- In the diagnosis phase, the critical examination of the canal state and the way it is operated yields significant physical evidence on the ground of what is really happening in terms of management organization and service to users.
- In the development of the modernization plan, canal operation is critical as the intervention aims to achieve the agreed upon and/or upgraded service. Many irrigation reforms have learned how important canal operation is the hard way, by neglecting it in the design of both infrastructure and management setup. Modern design concepts are based on the definition of an operation plan to achieve specific service and performance objectives.

Users are central to this Service Oriented Management (SOM)-based approach. The way the various steps of MASSCOTE are developed aims to generate practical options and solutions for service and operations on which the users will have to decide. It is fair to say that canal operation is the focus and entry point of MASSCOTE, while its overall goal is modernization of management with the users as central actors.

Canal operation is a complex set of tasks involving many critical activities that have to be undertaken in a consistent and timely manner for good irrigation management. Among the numerous aspects of management, the following need to be considered:

- service to users;
- cost and resources dedicated for operation and maintenance (O&M);
- performance monitoring and evaluation (M&E);
- constraints on the timing and amount of water resources;
- physical constraints and opportunities relating to topography, geography, climate, etc.

There is no single answer as to how to integrate all the elements into an effective and sustainable framework for improving canal operation. However, the new MASSCOTE approach has been developed on the basis of extensive experience with irrigation modernization programs in Asia between 1998 and 2006. MASSCOTE aims to organize the development of modernization programs through a step-by-step methodology:

- mapping various system characteristics;
- delimiting institutionally and spatially manageable subunits;
- defining the objective for service and strategy for and details of operation for each subunit.

A STEP-BY-STEP FRAMEWORK

The first MASSCOTE steps [steps 1 to 6] outlined in Figure 1 are to be conducted for the entire Command Area (CA). The goal is to identify uniform managerial units for which specific options for canal operation can be designed and implemented.

Step 1: Mapping the Performance: the Rapid Appraisal Procedure (RAP)

An initial rapid but comprehensive appraisal is the essential first step of the MASSCOTE approach. The RAP is a systematic set of procedures and indicators for diagnosing the bottlenecks of performance within an irrigation system (FAO, 1999; IPTRID 2001).

The RAP internal process indicators assess quantitatively the internal processes, i.e. the inputs (resources used) and the outputs (services to downstream users), of an irrigation project. Internal indicators are related to operational procedures, management and institutional setup, hardware of the system, water delivery service, etc. They enable a comprehensive understanding of the processes that influence water delivery service and overall performance of a system. Thus, they provide insight into what could or should be done in order to improve water delivery service and overall performance (assessed by the external performance indicators).

The RAP external performance indicators compare input and output of an irrigation system and are expressions of various forms of efficiency, e.g. water-use efficiency, crop yield, and budget. They do not provide any detail on what internal processes lead to these outputs and what should be done to improve the performance. However, they could be used for comparing the performance of different irrigation projects, nationally or internationally. Once these external indicators have been computed, they could be used as a benchmark for monitoring the impacts of modernization on improvements in overall performance.

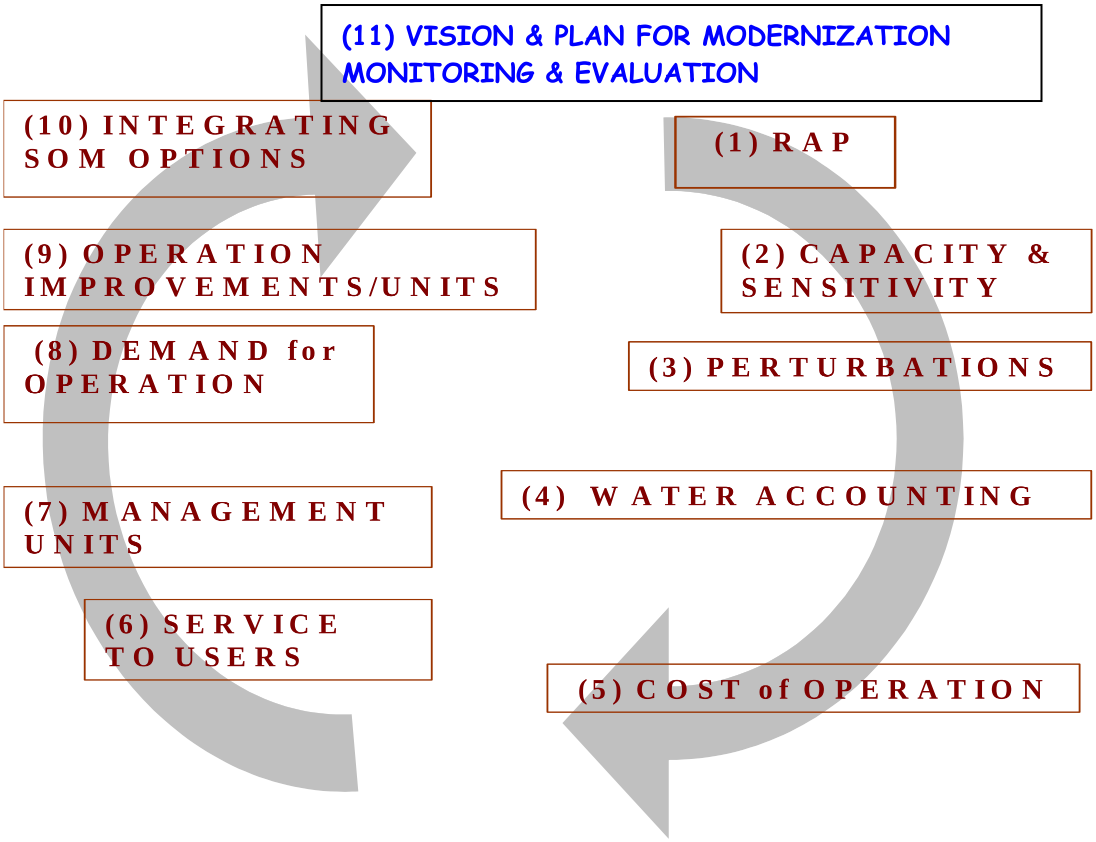


Figure 1. The 10+1 Steps in the MASSCOTE Approach

Step 2: Mapping the System Capacity and Sensitivity

Mapping the system capacity and sensitivity deals with features of the physical infrastructure including the function of structures for conveyance, water level or flow control, measurement, and safety. Irrigation structures are intended to perform a particular function. How they are designed, installed, calibrated and maintained results in specific performance characteristics – some designs are better than others depending on the situation – and actual conditions may change with time owing to various phenomena, such as erosion, siltation and rusting.

Mapping Capacity. It is important to have a reasonable assessment of the existing status of the system in performing the basic functions. Specifically, it is critical to identify any weak points, bottlenecks and/or areas with particular deficiencies. The mapping assessment of the flow capacity of infrastructure is necessary in order to compare with the design, but more importantly to ensure that the whole system is consistent with the operations plan to be developed.

Any major structural deficiencies need to be addressed as part of the planning process of modernization. Modernization improvements cannot be carried out successfully without dealing with the impacts of severely degraded or dysfunctional infrastructure.

Mapping the Sensitivity. the sensitivity of irrigation structures (offtakes and cross-regulators) is determined, along with the identification of singular points. Mapping of the sensitivity at key locations is crucial in managing perturbations.

The basic idea is to know where the sensitive offtakes and regulators are located, which subsystems propagate the perturbations and which ones absorb them. Thus, in terms of mapping:

- mapping of structures: sensitive regulators and sensitive offtakes;
- mapping of subsystems: average characteristics per subsystem – sensitive for flow control and water-level control.

This step gives rise to the following obligations and options relating to sensitive structures/subsystems:

- sensitive structures must be checked and operated more frequently or may have to be replaced with less sensitive structures;
- sensitive structures can be used to detect fluctuations (part of information management);
- sensitive subsystems can divert perturbations into subareas or through offtakes for which vulnerability is low.

Sensitivity indicator of irrigation structures: The sensitivity of an offtake refers to the function of generating an assured discharge in a dependent canal from a certain water level in the parent canal whereas for a cross regulator it refers to controlling water level in a canal. Table 1 in Appendix 1 summarizes the information about the irrigation structure sensitivity indicators (Renault, 1999).

Mapping sensitivity for irrigation structures can be achieved through: (i) direct measurement; (ii) analysis of flows records; and (iii) hydraulic formula. The last is the easiest option as it only requires knowledge of the flow type and the head on the structure. Sensitivity indicators for Offtake and Cross-regulators are estimated by the following equations:

$$S_{Offatke} = \frac{\alpha}{\text{head}} \quad \text{(unit: m}^{-1}\text{)} \tag{1}$$

$$S_{Regulators} = \frac{head}{\alpha} \quad \text{(unit: m)} \tag{2}$$

where α is the exponent in the hydraulic equation of the flow through the structure; α equals 1.5 for overshot flow and 0.5 for undershot flow. A structure is considered low sensitive if $S \leq 1.0$; moderately sensitive if S = 1.0 to 2.0; and highly sensitive if S >2.0.

Sensitivity and operational rules**:** one of the purposes of assessing the indicators of sensitivity is to define canal operation rules such as tolerance on water control and frequency of checking.

This is illustrated through an example taken from Sunsari Morang Irrigation Project (in the Terai of Nepal): sensitivity indicators have been assessed at main nodes (a node is composed of a cross-regulator and a major offtake to a secondary canal). Values (plotted in figure 2) are used to determine tolerance of water control and frequency of checking (see table 1) to achieve a target control of flow rates.

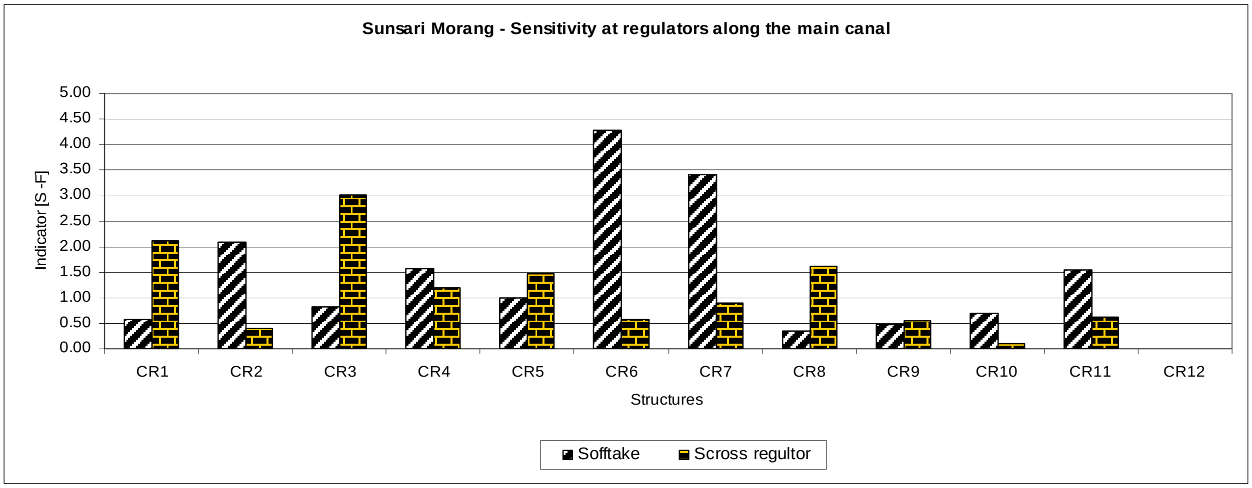


Figure 2. Measured Sensitivity Indicators at Cross Regulators of Main Canal SMIP Nepal-Terai

Table 1. Operation Rules - Tolerance and Frequency of Adjustment (Derived from Sensitivity Analysis SMIP Nepal Terai)

Cross regulator	Features	Tolerance on water level control	Frequency of adjustment of the CR
CR1	S regulator is high (2 m) S offtake low (0.6 m^{-1})	Tolerance 0.1 m acceptable	More frequent adjustment
CR 2	S regulator is low (0.4m) S offtake High (2 m^{-1})	Reduced tolerance should be sought (± 5 cm)	low frequency enough
CR3	S regulator is very high (3m) S offtake low (0.8 m^{-1})	Tolerance 0.1m acceptable	More frequent adjustment
CR4 and CR 5	S regulator average (<1.5m) S offtake average (<1.5m^{-1})	Tolerance 0.1m acceptable	Average frequency adjustment
CR6 and CR 7	S regulator is low (<1m) S offtake high (>3.5 m^{-1})	Reduced tolerance should be sought (below 5 cm) which might be difficult to achieve. Reducing the sensitivity of offtakes should be considered.	Average frequency adjustment
CR8 to CR11	S regulator is average or below S offtake is average or below	Tolerance 0.1m acceptable	Average frequency adjustment

Step 3: Mapping Perturbations

Perturbations refer to a significant change in the flows occurring along a canal network as a result of external variations in inflows or outflows, changes or adjustments in the settings of structures, or transient flow during distribution changes. Perturbations of water variables (level and discharge) along an open-channel network and unsteady state are the norm not the exception. Despite being a target for canal operation between changes in deliveries, steady state along a canal is rarely found in practice. Thus, perturbation is a permanent feature of irrigation canals caused by setting of upstream structures and compounded by intended or unpredicted changes in inflows/outflows at key nodes.

Thus, if perturbations are unavoidable, then the only option for managers is to have a reliable knowledge of their origins, and to know how to detect and manage them. Managing a canal also deals with uncertainties and instabilities.

Perturbations can be either positive or negative, representing an increase or decrease in discharge, respectively. The types and characteristics of perturbations that need to be mapped are:

- positive perturbations:
  - nature (inflow-outflow – internal),
  - magnitude (water-level fluctuation – relative discharge variation),
  - frequency;
- negative perturbations:
  - nature (inflow-outflow – internal),
  - magnitude (water-level fluctuation – relative discharge variation),
  - frequency.

With positive perturbations, the management options are:

- respond by acting on the supply;
- share the surplus proportionally among users;
- divert and store the surplus into storage capacity.

With negative perturbations, the management options are:

- compensate from storage;
- check for immediate correction;
- reduce delivery to some offtakes, with compensation later on (less sensitive/vulnerable areas, delivery points with storage facilities, with alternatives source of water).

Step 4: Mapping the Water Networks and Water Balances

In this step, the concept is to map the surface water network including irrigation and drainage layout, but also any natural channels if they interact or may interact in the future with the canal system and/or storage facilities. The objective is to know where and when all the inflow points to and outflow points from the service area occur in terms of flow rates, volumes, and timing. This mapping includes all safety structures built to evacuate surplus water to the drainage network.

The water balance of course also includes groundwater (recharges and abstractions). Although MASSCOTE focuses on canal operation, present conjunctive use within the system and conjunctive use as an option to recirculate water, improve efficiencies, or achieving a high service standard is fully considered.

Managers must have accurate knowledge about all the paths of water – where it is coming from and where is it flowing to, and in what volume. Knowing the water balance of the system is important not only for achieving high efficiencies but also for tackling environmental issues such as waterlogging and salinity buildup. It is also a good management tool for transparent water distribution within and among subareas of a system.

Estimation of inaccuracies in assessing the terms of the water balance is critical in particular with the closure of the balance (Burt, 1999, Clemmens and Burt, 1997) which is often known with high uncertainties.

Mapping of the water balance is important at each management level. Therefore the process within MASSCOTE is iterative: the first water balance should be carried out at the entire gross command areas (step 1 of the RAP in fact already includes a water balance with available information), and then at the local management agencies that result from the partitioning in step 7.

Step 5: Mapping the Cost of O&M

In this step, mapping is done of the costs for current O&M. It also involves disaggregating the elements entering into the cost and developing costing options for various levels of services with current techniques and with improved techniques.

In order to produce the service that has been decided/agreed upon with users, managers need to mobilize a set of various resources or inputs, such as water, staff, energy, office, communication, and transport. All of these entail a cost. This step aims at clarifying the issue of inputs and costs for operation as part of the overall management activities and as fundamental elements of the modernization process.

Investigating inputs and costs is important for:

- setting the service levels, in particular in exploring options for different types of services and associated costs;
- water pricing to users, in order to propose a set of charging procedures that takes into account the real cost of service production;
- improving performance and cost-effectiveness, by investigating technical options for maximizing operational effectiveness (better allocation of existing resources, automation, etc.).

Mapping the cost for operation and maintenance is usually difficult mainly because of lack of information. The figures on cost of different components (such as operation, staff, maintenance etc.) are often lumped together and disaggregating for operation and for services is not straightforward.

Step 6: Mapping the Service to Users

The services to users are today much broader than at the initial stages of irrigation development although water demands by farmers are still central. In the extended category of services within an irrigation project, the following services can be found:

- domestic supply to villages;
- recharge to groundwater;
- environmental flows;
- health;
- industrial uses;
- fishing;
- recreational areas;
- tourism.

The task of defining the service and determining the requirements for operation consists of clearly defining the service and the consequent requirements for operation.

From the previous steps, a preliminary vision of the scheme can be proposed for the near future, from which the preliminary features of the water services in the CA are derived:

- How many categories of service are considered, and how are these spatially distributed?
- How are the services evolving with time throughout the year?
- What is the service for crops with respect to the different seasons?
- What is the flexibility in defining the services with respect to the resources constraints?
- What are the features of allocation, scheduling and water deliveries that define the overall service?

Assessing all the different services provided to different users and their related costs are what need to be mapped in this step. Mapping of service is required for further analysis of modernization opportunities and economic analyses to be done in later steps.

Step 7: Mapping the Management Units – a Subunit Approach

Large canal irrigation systems serving large areas are usually divided into smaller manageable units called tracks, blocks and subsystems. In the past (and particularly for new systems), these management units have often been based on the hierarchy of the canal network (main, secondary, tertiary, etc). Today, with the increasing complexity of management and operation needed to provide higher levels of service; this partitioning might be less relevant than it was when the systems were originally constructed. There are more relevant operational criteria on which subunits should be based such as:

- Participatory management;
- Spatial variation of water services;
- Conjunctive water management and boundaries for water balance;
- Multiple users of water;

- Drainage conditions;
- Recirculation patterns and opportunities;
- Specific points along the infrastructure.

Subunits of operation/management should define an area for which a certain relatively homogeneous level of service is agreed upon and provided, and for which the water balance is to be managed as a single unit. A workable compromise has to be found between the physical/hydraulic system and the institutional/managerial resources in each subunit. Figure 3 presents an example of partitioning of a command area into sub-units.

The rationale for determining appropriate subunits takes into account multiple considerations. However, the setting up of too many units should be avoided, keeping in mind the baseline costs associated with the management of individual units and the non-viability of very small units.

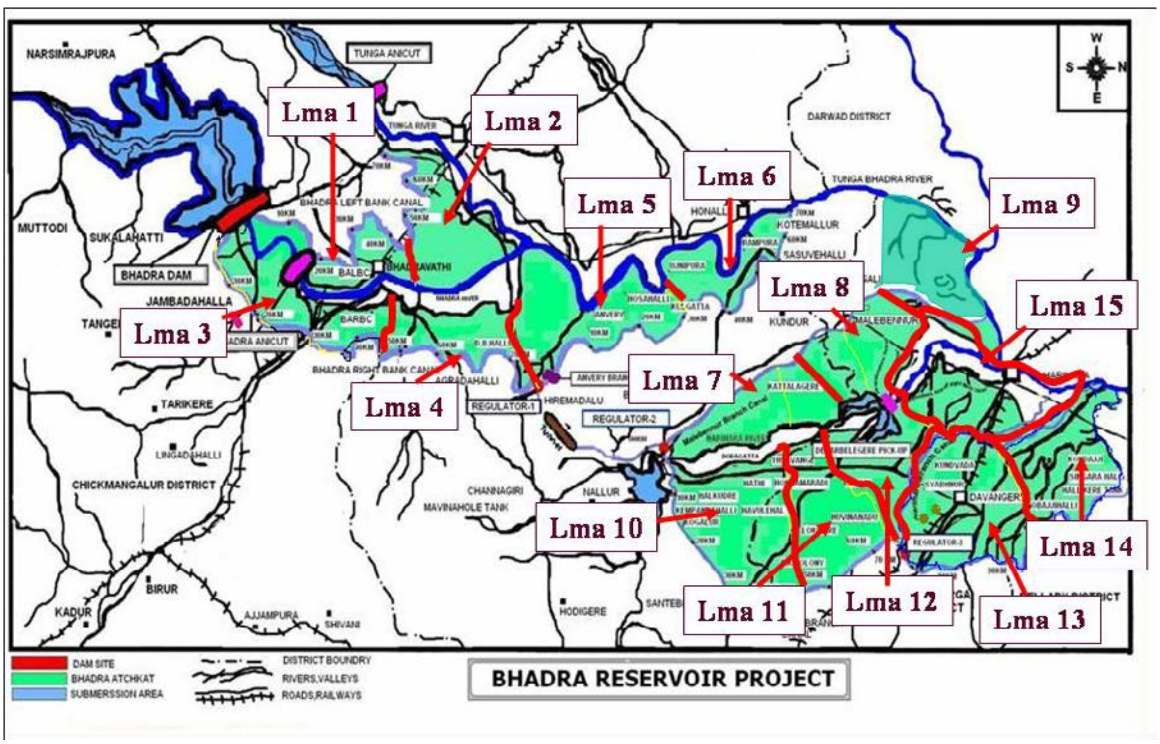


Figure 3 . Example of Partitioning with Reservoir & Main Canal into One Single Unit and CA Split into 15 Local Management Agencies (Average 7000 ha) [Bhadra Project Karnataka India]

Step 8: Mapping the demand for operation

This step involves assessing the resources, opportunity and demand for improved canal operation. It entails a spatial analysis of the entire service area, with preliminary identification of subsystem units (management, service, O&M, etc.).

Assessing the requirements for canal operation needs to be done alongside and in combination with the definition of the service by users and stakeholders. However, canal operation

requirements cannot be derived directly from service demands. The system presents opportunities and constraints that set the boundaries for possible modes of operation. In short, the requirements for operation will depend on three domains: (i) the service will specify the targets; (ii) the perturbation will specify the constraints in which the system operates; and (iii) the sensitivity will specify how fast the system reacts to changes and produces changes when left un-operated.
The rationale is straightforward: the higher the sensitivity, perturbations and service demand, the higher the demand for canal operation. This can be expressed in the relationship:

$$\text{Demand for operation} = \text{service} \times \text{perturbation} \times \text{sensitivity} \qquad (3)$$

<u>Step 9: Mapping Options for Canal Operation Improvements: Main System and Subunits</u>

This step entails identifying options for improvements to main and secondary canal operations. Improvements should aim at specific objectives such as:

- improving water delivery services to agriculture users;
- optimizing the cost of operation;
- water conservation;
- integrating the multiple uses of water (IWRM).

Here the methodology is carried out in two complementary and converging ways or double sweeping i) at the main system serving the sub-units and ii) at each sub-unit considered initially as an autonomous system served by the main system.

Modernization improvement options are investigated for each unit (main and subunits) based on: (i) water management; (ii) water control; and (iii) canal operation (service and cost-effectiveness).

The improvements are to be sought through one or a combination of the following options:

- allocating existing resources and inputs in a more cost-effective and responsive manner;
- optimizing the organization and the operational modes;
- changing the operational strategy;
- investing in improved techniques and infrastructure.

For water management, the improvements aim to increase water use and productivity by: (i) minimizing losses; (ii) maximizing water harvest; and (iii) re-regulating storage.

For water control, the improvements concern the hydraulic configuration of the operations. This entails a sequence of: (i) fine-tuning the hydraulic heads of canal structures in relation to each other; (ii) creating a specific hydraulic property of the canal (section) so that it performs as intended; and (iii) choosing the option that will minimize manual operational interventions/regulations for a specific period.

Step 10: Integrating and Consolidating the Service-Oriented Management Options

Improvement options for the main canal system and subunits are finalized together with the associated costs for every option. The options for the sub-units are then confronted and aggregated at the main system level, and checked for consistency with the finalised improvement options at the main system level. A short-term modernization strategy is laid out with objectives and proposed achievements/improvements.

Step 11: Vision and Plan for Modernization and M&E

The carrying out of the previous steps with some reiterative cycle is the process by which, progressively, a vision of the near future for the irrigation scheme is crafted and consolidated.

This vision must then be converted into a plan that should aim at achieving the vision. A first phase of modernization improvements that meets expectations and aims at potential achievements at a realistic and practical level must be implemented in order to successfully initiate a long –term modernization process. A decision about the options to pursue is taken through extensive participation of the users. The solutions that are easiest and most cost-effective to implement are to be selected to start the process of modernization.

The establishment of long-term vision, modernization strategy, and plan for the system is outside the scope of MASSCOTE and needs to be supported by a thorough strategic planning process.

Monitoring and evaluation of the improved operations are necessary in order to ensure that achievements are maintained, and to provide a basis for comparison of the situation before and after the improvements.

IMPORTANT FEATURES OF MASSCOTE

There are four important features to bear in mind about MASSCOTE.
The first is the embedded nature of the RAP and MASSCOTE within a short-term modernization project (Figure 2) that requires a modicum of additional resources.

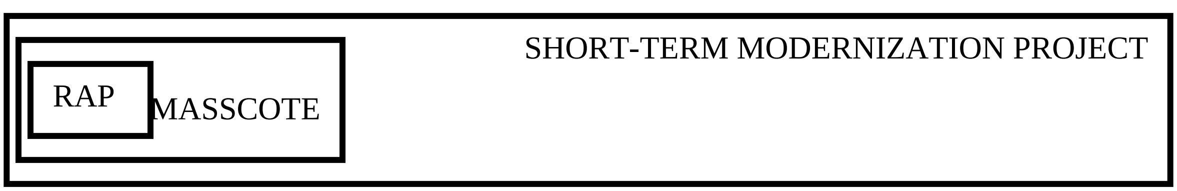


Figure 2. Embedded Nature of the RAP and MASSCOTE

The second feature concerns the different time frames of the interventions:
- RAP = week;
- MASSCOTE = month;
- Short-term modernization project = year;

- Medium and long term vision and modernization plan: 2-3 and 5 to 15-30 years, respectively. These may require more fundamental restructuring and mobilization of substantial additional resources.

The third feature concerns the revolving nature of MASSCOTE. This might imply iterative circles before reaching a consolidated stage of analysis and project – several rounds of MASSCOTE at different levels of the system (main supply, subunits) before integrating at the main supply and subunit level.

The fourth feature is that a major entry point of the MASSCOTE methodology is canal operation for diagnosis and for designing improvements. However, the overall objective in carrying out a MASSCOTE exercise is modernization of management. Canal operation is a critical entry point because: (i) it is the activity that puts management decisions into tangible outputs; and (ii) it is there that the current management performance is sanctioned and expressed in the most obvious manner (its symptoms). MASSCOTE evolves from canal operation to management options (institutional partitioning, organization, and SOM). A longer-term plan will address more systematically other issues related to management such as incentive structure, governance, and financing in a full-fletched asset management plan.

MASSCOTE APPLICATIONS IN CAPACITY BUILDING PROGRAMS

In 2006 and 2007 the MASSCOTE approach has been applied successfully on 10 irrigation systems. The capacity building approach was based on the following ideas: modernization should follow a holistic and step-wise approach, tailored to a detailed assessment and constraints of each individual system. To go beyond the measurement and analysis stages and on to the implementation of changes and improvement stages, there must be significant acceptance by project personnel, identification of weaknesses and potential changes, and knowledge of options for change. The carrying out of an initial appraisal with a Rapid Appraisal Procedure and a more detailed step-wise methodology with MASSCOTE are thus incorporated into the training program that integrally involves local management and operation and maintenance staff. Staff learn the concepts, are provided with a toolbox of options, evaluate their own project, and then develop a modernization strategy and detailed plans to improve operation and management for their project. This is meant to obtain support from staff, address the real issues in the system and avoid managers to be on the receiving end of standard modernization packages determined by outsiders. Modernization focuses in particular on making it easier, simpler, and more economical to achieve improved performance and is an important factor in buy-in from staff in terms of benefits that accrue to them, in addition to the core objective of improving performance and service to farmers. Those who provide funding (agencies and farmers) are also critical beneficiaries.

Immediate follow-up action requires strong leadership at agency level and at system manager level. Rigid design standards and lack of management decentralization are major factors in hindering change. However in the longer term, training does generate a shift in perceptions and concepts which may form a basis for a structured modernization program. Inputs from lower levels of operation and management, including water users associations, strengthened by training, anchoring, and design of details of modernization policies and strategies on specific hardware and software issues arising from systematic appraisals hold the promise of achieving actual improvements.

REFERENCES

Burt, C.M. 1999. Irrigation water balance fundamentals. Paper presented at the conference *Benchmarking irrigation system performance using water management and water balances*, pp. 1–13. ITRC Paper 99-001. Denver, USA, USCID.

Clemmens, A.J. & Burt, C.M. 1997. Accuracy of irrigation efficiency estimates. *J. Irrig. Drain. Eng*., 123(6).

FAO, 1997. Modernization of irrigation schemes: past experiences and future options, FAO-RAP 1997/22, Water Report Series 12, Bangkok, 1997

FAO. 1999. *Modern water control and management practices in irrigation: impact on performance*, by C.M. Burt & S.W. Styles. FAO Water Report No. 19. Rome. 224 pp.

FAO 2007. Modernizing irrigation management – the MASSCOTE approach: Mapping Systems and Services for Cana; Operation Techniques

IPTRID. 2001. *Guidelines for benchmarking performance in the irrigation and drainage sector*, by H. Malano & M. Burton. Rome.

Renault, D. 1999. Offtake sensitivity, operation effectiveness and performance of irrigation systems. *J. Irrig. Drain. Eng*., 125(3).

APPENDIX 1

Table 1. Summary of Sensitivity Indicators for Offtakes and Cross-Regulators

	OFFTAKE	CROSS-REGULATOR
Definition	The ratio of the relative variation in discharge through the offtake ($\Delta q/q$), to the variation in water level in the parent canal (Δh)	The ratio of the resulting variation in water level in the parent canal (Δh) when main discharge *(Q)* varies of *(ΔQ)*
Mathematical expression	$S_{Offtake} = \frac{\Delta q / q}{\Delta h}$ (unit: m^{-1})	$S_{\text{Regulator}} = \frac{\Delta h}{\Delta Q / Q}$ (unit: m)
Assessing Estimator	Derived from the equation[4] of the flow through the structure. $q = M(\text{head})^{\alpha}$ A robust estimator[5] of the sensitivity indicator is: $S = \frac{\alpha}{\text{head}}$ (unit: m^{-1})	Derived from the equation of the flow through the structure. $q = M(\text{head})^{\alpha}$ A robust estimator of the sensitivity indicator is inverse to that of the offtake : $S = \frac{head}{\alpha}$ (unit: m)
Use	estimating the reaction of an offtake $\Delta q / q = S_{Offtake} \cdot \Delta h$	for estimating the variation of water level resulting of a given discharge variation $\Delta h = \frac{\left(\Delta Q / Q\right)}{S_{\text{Re}gulator}}$ (unit: m)
Use	for evaluating the tolerance of water control for a target of discharge variation $\Delta h_{permissible} = \frac{\left(\Delta q / q\right)_{set}}{S_{Offtake}}$ (unit: m)	Detecting variation of main discharge by noticing variation of water level at sensitive regulators.
Example	an offtake with a sensitivity = 2, experiences 20-percent variation in discharge when water level upstream varies by 10 cm	a cross regulator with a sensitivity = 3 will experiences a variation of upstream water level of 30 cm when main discharge varies by 10 %
Range of indicator	A structure with a sensitivity indicator $S < 1$ is considered low, medium between 1 and 2, and $S > 2$ indicates a highly sensitive structure.	

[4] *M* is a value independent of the head exercised on the structure. *M* depends on the shape, size and hydraulic coefficients of the flow through the structure. Head is the head exercised on the structure (water level upstream minus the water level downstream if the structure is submerged, or minus a level of reference taken as the crest level for overshot structure or the orifice axis for undershot if the structure is not submerged). α is the exponent in the relevant hydraulic equation for flow; α equals 1.5 for overshot flow and 0.5 for undershot flow.

[5] When the structure is submerged, the flow is governed by two equations and a correcting factor should be introduced. However the order of magnitude of the indicators is conserved and that is enough. Only for high sensitivity indicators correction is needed.

AN OPEN CHANNEL NETWORK MODERNIZATION WITH AUTOMATED STRUCTURES

J. Natividad Barrios-Domínguez[1]
Carlos F. Bautista-Capetillo[1]
Eduardo Bautista[3]
Francisco Mojarro-Dávila[1]
Nahún H. García-Villanueva[2]
Julián González-Trinidad[1]
Adalberto Castro-Ávila[1]
Dagoberto Chávez-Carlos[1]

ABSTRACT

In Mexico, most irrigation delivery systems consist of a network of open-channels with manually-operated control structures. Efficiencies of these systems typically are low. To improve water management in these systems, the Mexican government has attempted to modernize many irrigation projects (Reynosa, Apatzingan, Valle del Mezquital, and Santiago among others).using automatic self-leveling check structures However, problems have emerged with the operation of these structures, causing dissatisfaction among water users.

The Santiago Irrigation System (SIS) began operating in 1998. Its main distribution system consists of open channels regulated by self-leveling gates and constant flow modules. Low-pressure pipelines deliver water to individual plots. During the first three years of operation, inadequate water level regulation with the automated gates caused water distribution problems that ultimately affected crop productivity. This negative situation encouraged users to take control over the irrigation system and to revert to the traditional manual operation.

To help address the technical issues, an experimental channel was built at the University of Zacatecas. The channel was expected to help researchers develop a better understanding of the hydraulic theory and operation of this type of structures and to help solve practical installation and operational problems. This paper describes our experience rehabilitating and calibrating AVIS and AVIO self-leveling gates; it also describes the sequence of operations that must be followed for the adequate management of the automated structures in the SIS main network.

Keywords: Self-leveling gates; Modernization; Operation efficiency

INTRODUCTION

Water application for agricultural purposes in adequate time and amount plays a fundamental role in crop yield. On the other hand, water availability for irrigation has been reduced in past years due to severe and extended droughts (Rosano-Méndez et al. 2001). About 70% of the

[1]Hydraulic Engineer. Maestría en Planeación de Recursos Hidráulicos, Universidad Autónoma de Zacatecas. Av. Ramón López Velarde No. 801 CP: 98000, Centro Zacatecas, Zacatecas, México. Tel: (492) 9239407 ext. 1617, 1623.nati@uaz.edu.mx; baucap@uaz.edu.mx; jgonza@uaz.edu.mx; acasav5@yahoo.com; dagoch@uaz.edu.mx; fmojarro@inifapzac.sagarpa.gob.mx.
[2]Hydraulic Engineer. Instituto Mexicano de Tecnología del Agua. Paseo Cuauhnáhuac No. 8532 Colonia Progreso Jiutepec, Morelos, México CP 62550. nahung@tlaloc.imta.mx.
[3]Research Hydraulic Engineer. USDA-ARS Arid Land Agricultural Research Center 21881 North Cardon Lane. Maricopa, AZ 85239. Tel. (520)316-6381, Fax (520) 316-6330. EBautista@uswcl.ars.ag.gov

current worldwide water withdrawal is used for irrigation (FAO 2003). Global efficiency in irrigation projects in Mexico is less than 50% (CNA, 2006). A factor contributing to low efficiencies is the distribution of water through irrigation networks. In Mexico, most irrigation conveyance and distribution systems consist of a network of open channels controlled by manually operated control structures. Operation of these systems is typically based on empirical concepts and operator experience. Water deliveries to farms frequently do not match irrigation requirements as the volume delivered depends on the operator’s judgment.

In countries such as France, Spain, and Italy one alternative that has been used to improve canal operation and water delivery service is the use of automated control with self-leveling gates (Guillén et al. 2000). In theory, these structures enable more predictable and equitable water distribution since they do not require continuous manual adjustments. The Mexican government has modernized several irrigation projects using this technology (Reynosa, Apatzingan, Valle del Mezquital, and Santiago). Performance of some of these systems has been disappointing as a result of design and installation problems and the lack of experience by operators and water users with the use of self-leveling gates. A better understanding of the technology is needed in order to get the most benefits and overcome its limitations.

The objective of this article is to summarize our experience with the development and implementation of an integrated operational plan for the irrigation project of Santiago, Zacatecas. This irrigation project began operating in 1998 and currently services about 600 hectares. During the initial years, operation of the conveyance and distribution network faced numerous technical and organizational challenges that ultimately led to conflicts among users and low global project efficiency.

BACKGROUND

The Santiago Irrigation System (SIS)

The study area is located within the Ejido (communal land) “Miguel Auza,” in the northwest of the State of Zacatecas, Mexico (Figure 1). Geographic coordinates are latitude of 23^{o} 17’ 52’’N and longitude 103^{o} 27’ 36’’W, and the elevation is 1,898 m AMSL.

Average annual rainfall in northwest Zacatecas is less than the water requirements for crops that can be grown in the region; therefore, the SIS was built to provide supplementary irrigation. The National Water Commission (CNA, from its Spanish acronym) conducted hydrologic, engineering, and feasibility studies in the area in 1990 and began building the system in 1991. When the delivery system was completed in 1998, it irrigated 100 ha; today it services an average of 600 ha per year. Predominant crops are corn, chili, beans, and alfalfa. The system supplies 306 users with an average farm size of 2 ha. Agriculture is a secondary economic activity for most users, as most work in construction, commerce and services. Production is mostly self-consumed or used as feed, but occasional surpluses are sold in regional markets.

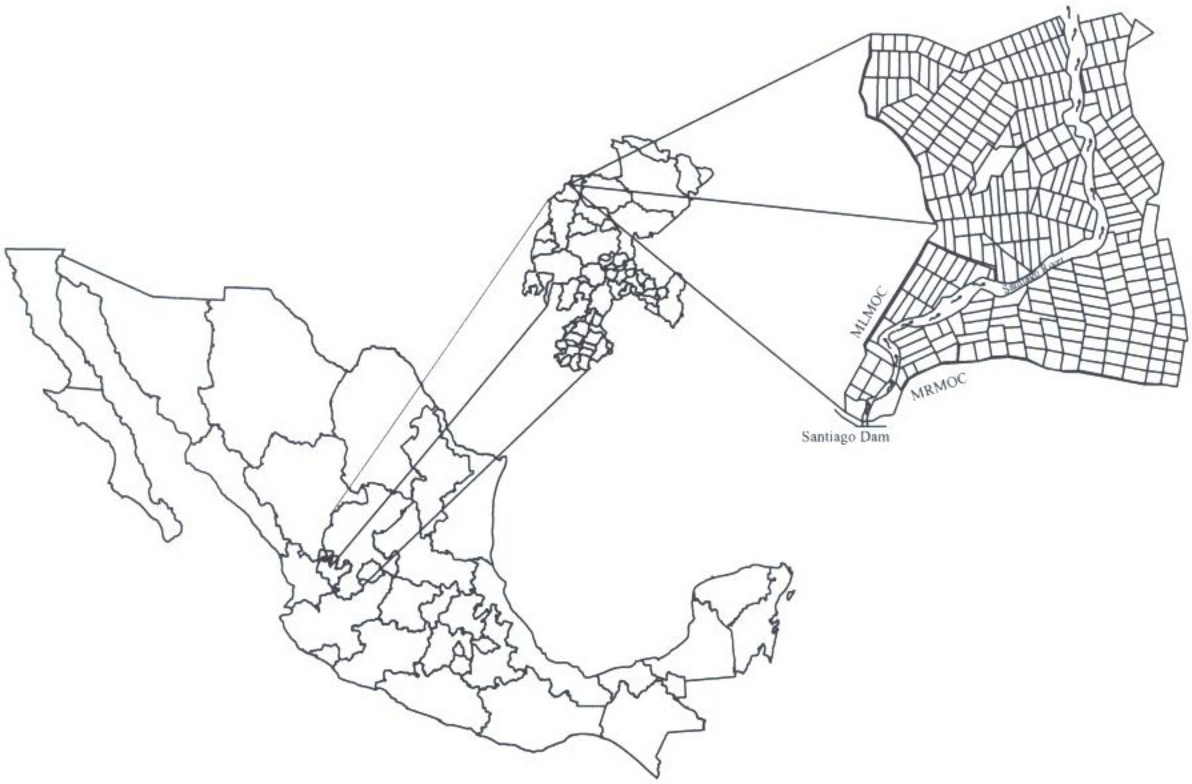


Figure 1. Location of the Santiago Irrigation System

The users are legally organized in a Water User Association (WUA). A six-member Board of Directors (BOD) represents their interests before the federal government (represented by the CNA), state government, and the private sector. The WUA elects the Board every three years and all Board members are registered users. The SIS administrative and operational staff consists of an accountant, a technical manager, and two CNA-certified ditch-riders.

The SIS Technical Manager and the BOD together develop the operational plan for the water year October 1-September 30, which must be approved by the CNA. The plan includes forecasts of the yearly cropping pattern and monthly delivery volumes needed to meet crop water demands. CNA delivers water to the SIS headgate based on this plan, and SIS distributes of this water to users through its network. The CNA is responsible for monitoring reservoir storage and for making adjustments on bimonthly basis based on actual storage levels and deliveries.

The delivery system has two main channels, the Right and Left Margin Channels, with a capacity of 0.798 and 0.771 m^3/s, respectively. Unlike most Mexican irrigation projects, which were built for upstream control with manually operated cross-regulators, the SIS was built for downstream water level control with self-leveling gates. Water is delivered through offtakes equipped with constant-flow modules which are also used for flow measurement. Each offtake is designed to supply water to 10 ha, and thus they service between 4 and 5 users.

The original plan was for the SIS to operate as a constrained arranged delivery system, with a fixed delivery flow rate at each turnout, 30 l/s (the design Unit Irrigation Flow Rate). Users were expected to submit their water orders to ditch-riders either Monday through Wednesday for deliveries on Thursday and Friday, or Thursday through Saturday for Monday through Wednesday deliveries. From these orders, the technical manager was then expected to develop the daily schedule of deliveries, including the starting and stopping time for delivery to a turnout, and the schedule of canal operations to be followed by the ditch-riders.

Upon completion, the CNA turned over the canal system to the user association in 1998, assuming that the users would only encounter minor problems in operating the system with the self-leveling gates and that they would be able to easily solve those problems on their own. Lack of experience in the operation of these hydraulic networks, and in particular a lack of understanding of the installation and operation of self-leveling gates created immediate difficulties. Because of the resulting inequitable and untimely deliveries, crop yields were affected in the initial year of operation and conflicts emerged among users.

Evaluation of the Santiago Irrigation System

The Autonomous University of Zacatecas (UAZ), through its Hydraulic Resources Planning program, built an experimental channel in the year 2000 for the purpose of demonstrating and researching canal control concepts with self-leveling gates and to provide training on those concepts to irrigation system operators. The channel was built with technical and economic support of the Mexican Institute of Water Technology (IMTA) and the Spanish Agency for International Cooperation (AECI). This channel is 70 meters long, with a 1.00 X 0.85 meter rectangular cross section, and is equipped with self-leveling structures for upstream and downstream water regulation. With the channel, UAZ researchers have been able to establish criteria for the installation, calibration and operation of AVIS, AVIO and AMIL gates.
Given the problems experienced at the SIS and the expertise available at the UAZ, the CNA entered into a collaborative agreement in 2001 with IMTA and UAZ to conduct a systematic assessment of the Santiago Irrigation System and develop a plan to improve its operation. CNA agreed to fund the project while IMTA and the UAZ agreed to define the research methodology and provide the needed technical resources. The WUA agreed to adopt the resulting recommendations.

The assessment was carried out in three stages: diagnosis, development of solution alternatives, and dissemination of results. The Rapid Appraisal Process (RAP) (Burt, 2001) was selected as the diagnostic methodology. Part of this process consists of a detailed field inspection to characterize the design, construction, and physical condition of the infrastructure. Another part of the process examines water allocation and delivery policies, operational procedures, and administrative procedures based on interviews with users and irrigation system staff.

Diagnostic Results

The following paragraphs summarize the key findings from the RAP:

- The capacity of the main network was found to be adequate for downstream water regulation. This capacity has to be greater than the maximum crop water demands. These demands were calculated using the Unitary Irrigation Coefficient (UIC) methodology (SARH, 1973). The UIC is calculated for different reaches of the network, based on their service area and predominant crops. The analysis confirmed that capacity exceeds peak demands, even though the system operates only for 11 hours of every day.

- Cross-regulators and offtakes were found to be in poor physical condition. The field inspection revealed damaged or worn-out structures (as is shown in Figure 2), and thus incapable of operating as designed. As a result, structures were being operated manually, and based on the criteria of individual ditch-riders. Installed self-leveling gates were evaluated and compared with AVIS and AVIO gates manufactured by Nerpyc GEC Alsthom. The gates satisfied minimum hydraulic design criteria, but problems were observed with installation and calibration. Hence, those structures were not performing as they were supposed to.

- Deficient operation of the network. Data collected during field visits and office interviews revealed that SIS operators lacked general training in downstream regulation and specific training in the operation of self-leveling structures. At the same time, CNA did not have technicians capable of calibrating the self-leveling structures. Clearly, technical support was needed to improve the system's operation but CNA was unable to provide that support.

- User dissatisfaction. Inadequacies of the delivery rules and in the implementation of those rules generated user dissatisfaction with the delivery service. First, the delivery constraints (with different users receiving water on different days) generated conflicts among users, as the needs of some of the users were not being satisfied; in addition, the ditch-riders were not following the daily plan, but were assigning instead irrigation turns and volumes arbitrarily. As a result, deliveries were inequitable.

- Lack of mechanisms to enforce user rights and responsibilities. The system started operating without written administrative procedures needed to enforce delivery and maintenance rules. Because of the lax enforcement, the SIS was having a difficult time collecting irrigation service fees and users were tampering with the control structures and taking water out-of-turn.

- A significant volume of water was being lost due to the discontinuous operation of the system. The system only delivers water during the daylight hours. Because control structures are not water-tight, water left in the canals at the end of the day leaks out. Table 1 shows an average in the occurred volume changes between the initial and final Margin Right Main Open Channel (MRMOC) operation for several consecutive days. In addition to the water loss, this mode of operation further reduces the delivery window, due to the time needed to refill the channel.

Figure 2. Damage and hydraulic instability of Self-Leveling Gates

Table 1. Volume Changes without MRMOC Operation During Consecutive Days

	Reach 1	Reach 2	Reach 3	Reach 4	Total
Reach Length (m)	320.00	1,000.00	1,100.00	320.00	
Side Slope	1.50	1.50	1.50	1.50	
Width Bed (m)	0.65	0.65	0.65	0.65	
Head (m)	0.93	0.93	0.73	0.58	
Longitudinal Slope (m/m)	0.0005	0.0004	0.0001	0.001	
Reach Volume (m^3)	611.66	1,950.45	1,394.94	300.49	4,257.54
Storage Volume (m^3)	0.00	53.20	347.08	300.49	700.76
Recover Volume (m^3)	611.66	1,897.25	1,047.86	0.00	3,556.78
Time for Volume Recovering Considering a 400 lps flowrate (min)	25.00	79.00	44.00	0.00	148.00

Integrated Operational Plan for Santiago Irrigation System

Irrigation projects modernization has been defined as a process of administrative and technical improvements of the irrigation system in combination with institutional reforms with the goal of improving the water delivery service to users and, ultimately, the use of resources (labor, water, economy and environment among others) and agricultural productivity (Burt, 1999). In the SIS case, initial efforts to calibrate and improve the operation of self-leveling gates led to the development of an integrated operation plan for the system. Based on the RAP results, administrative and technical proposals were formulated aimed at modernizing the system's operation. The proposals were analyzed by the CNA, the IMTA and the UAZ experts, as well as the SIS users. Proposed physical improvements included:

- Rehabilitation or replacement of damaged control structures, depending on their condition.
- Installation of control structures (AVIS or AVIO floodgates) where technically necessary.
- Preventing main channel water losses to reduce delays in water distribution.
- Measuring flows at the main channel headgates and at offtakes.

On the technology transfer side, the following actions were proposed:

- Training of operators in the calibration and operation of the self-leveling gates.
- Development of a practical guide for main channel operation, to be provided to both staff and users.
- Establishment of an educational program for users on the capabilities and limitations of the canal control systems and procedures.
- Evaluation of the operation system during its primary function months to correct deficiencies presented by the administration of the SIS.

RESULTS

The results of the physical improvements by implementing an integrated operational plan in the SIS were:

- Rehabilitation of eight control structures; damaged gate leaf, floaters, and support structures were replaced and the structures were repainted.
- Replacement of an installed self-leveling gate with a locally manufactured AVIO-type self-leveling gate. The replaced structure did not meet the design criteria of Nerpyc Gec Alsthom and was experiencing instability problems.
- Structures were calibrated by IMTA and UAZ experts to enable proper water level regulation following the methodology proposed by Nerpyc Gec Alsthom.

- To maintain water volumes in the open-channels network during all irrigation season, sliding gates were installed immediately upstream of every self-leveling gate as shown in Figure 3.
- To quantify offtake deliveries, a calibrated weir and sliding gates are used. Water flows to lateral off-takes are measured through constant flow modules.

Figure 3. Regulation and Control Structures before the Implementation of the Integrated Operational Plan

The integrated operation plan also produced changes in the delivery procedures, namely the users now present their water orders to the canal manager and the orders need to be submitted only one day in advance.

There has been a positive response by the water users to the integrated operational plan. Users are now more convinced about the ability of the system to provide the promised delivery service. Conveyance efficiency in has improved considerably partly due to elimination of canal water losses overnight, which created delays for the early deliveries, as shown in Table 2.

Table 2. Volumes Recovered in the MRMOC with the Integrated Operational Plan

	Reach 1	Reach 2	Reach 3	Reach 4	Total
Reach Length (m)	320.00	1,000.00	1,100.00	320.00	
Side Slope	1.50	1.50	1.50	1.50	
Width Bed (m)	0.65	0.65	0.65	0.65	
Head (m)	0.93	0.93	0.73	0.58	
Longitudinal Slope (m/m)	0.0005	0.0004	0.0001	0.001	
Reach Volume (m^3)	611.66	1,950.45	1,394.94	300.49	4,257.54
Storage Volume (m^3)	576.63	1,848.29	1,311.54	274.35	4,010.81
Recover Volume (m^3)	35.03	102.16	83.40	26.14	246.73
Time for Volume Recovering Considering a 400 lps flowrate (min)	1.50	4.25	3.50	1.1	10.35

Operations have improved also due to the practical operational guide, which outlines the different operational steps, including instructions for filling channels, initiating and stopping deliveries, procedures for correcting flows and levels. The guide also provides instructions for calibration of the self-leveling gates and of flow measuring weirs and sliding gates.

CONCLUSIONS

University of Zacatecas researchers developed significant experience in the design, installation, calibration and operation of self-leveling gates with the help of the experimental channel built in their hydraulics laboratory. With this experience, researchers were able to assist SIS staff and develop specific criteria for the installation and operation of these structures. Thanks to the operational plan, SIS users and staff now have a better understanding of the system’s capabilities and operation and have simplified their operational procedures. Flexibility of deliveries has improved, as orders need now to be submitted only one day in advance and users now can get service any day of week. The implementation of the integrated operational plan has reduced operational water losses and improved service, and as a result, users are making more productive uses of the available water.

REFERENCES

Burt, C. M. (1999). “Current Canal Modernization from an International Perspective”. Irrigation Training and Research Center, California Polytechnic State University, USA.

Burt, C. M. (2001). “Rapid Appraisal Process (RAP) and Benchmarking. Explanation and Tools”. Irrigation Training and Research Center, California Polytechnic State University, USA.

Comisión Nacional del Agua. (2006). “Estadísticas del Agua en México”. Secretaria de Medio Ambiente y Recursos Naturales. México.

Food and Agricultural Organization. (2003). “Irrigation Water”. Rome, Italy.

Guillén, G. J. A.; Lomelí, V. R. J.; Palacios, V. E.; Espinosa, M. R. and Ramírez, L. J. (2000). “Operación, Conservación y Administración de Módulos de Riego”, Comisión Nacional del Agua, Instituto Mexicano de Tecnología del Agua, México.

Rosano-Méndez, L.; Rendón, P. L.; Pacheco, H. P.; Etchevers, B. J. D.; Chávez, M. J. and Vaquera, H. H. (2001). “Calibración de un Modelo Hidrológico Aplicado en el Riego Tecnificado por Gravedad”. Agrociencia Vol. 35 December 2001, pp 577-588.

Secretaria de Agricultura y Recursos Hidráulicos (SARH) (1973). “Proyecto de Zonas de Riego”. Dirección de Proyectos de Irrigación, Departamento de Canales. México.

CANAL CONTROL ALTERNATIVES IN THE IRRIGATION DISTRICT 'SECTOR BXII DEL BAJO GUADALQUIVIR,' SPAIN

David Lozano[1]
Carina Arranja[2]
Manuel Rijo[3]
Luciano Mateos[4]

ABSTRACT

Improved water management and efficient investment on the modernization of the irrigation districts in most countries are imperative to satisfy the increasing demand of water. The automation and control of their main canals is one mean to increase the efficiency and flexibility of the irrigation systems.

In 2005, we monitored one canal in the irrigation district 'Sector BXII del Bajo Guadalquivir'. This is a representative irrigation canal of the irrigation districts in Southern Spain. This canal is divided into four pools and supplies an area of 5,150 ha. We used ultrasonic sensors and pressure transducers to record water levels upstream and downstream each canal pool. With the measured data and the hydraulic model SIC (Simulation of Irrigation Canals), we evaluated two canal control alternatives (local upstream control and distant downstream control) using a Proportional-Integral (PI) control algorithm. First, we calibrated and validated SIC under steady-state conditions. Then, we calibrated the proportional and integral gains of the PI algorithm. The obtained results show that only the distant downstream controller can quickly and automatically adjust the canal dynamics to unexpected water demands, with efficiency and no spills at the canal tail, even for sudden and significant flow variations.

Keywords: irrigation canal, local upstream control, distant downstream control, PI controller, water saving.

INTRODUCTION

Irrigation is the largest water user in the World. In Spain, irrigation uses about 75% of the available water. In addition, irrigation is now competing for water with the industrial, urban, recreational, and environmental sectors. Therefore, in order to save water and to provide better water delivery services, the irrigation sector must implement intelligent management and operation of the irrigation systems.

[1]Early Stage Researcher; Instituto de Agricultura Sostenible-C.S.I.C.; Alameda del obispo s/n, 14080, Córdoba, Spain; l52loped@uco.es
[2]Early Stage Researcher; Departamento de Engenharia Rural, Universidade de Évora/ICAM; Apartado 94, 7002-554 Évora, Portugal; carinaarranja@hotmail.com
[3]Hydraulic Professor; Departamento de Engenharia Rural, Universidade de Évora/ICAM; Apartado 94, 7002-554 Évora, Portugal; rijo@uevora.pt
[4]Research Scientist; Instituto de Agricultura Sostenible-C.S.I.C.; Alameda del obispo s/n, 14080, Córdoba, Spain; ag1mainl@uco.es

Due to technical and financial reasons, large water conveyance and delivery systems are usually open-channel systems. Water dynamics in open-channel canals are very complex and difficult to control, especially under a demand-oriented operation (Clemmens, 1987).

In Spain, the investment in the modernization of irrigation systems is notable. However, the interventions are focused mainly on the on-farm irrigation systems and on the transformation of the distribution systems from open canal networks to on-demand pressurized-pipe networks. In most cases, the modernization of the conveyance canals has been ignored or treated with little technical attention, and these canals remain the same as they were when first constructed decades ago.

Irrigation canal automation started with the use of self-controlled hydraulic gates -AVIS, AVIO y AMIL- (Kraatz and Mahajan, 1975). Later, electro-mechanical controllers emerged in the market and with them the first applications of control theory to the operation of irrigation canals (Shand, 1971). The introduction of personal computers allowed coupling canal flow simulation models with control algorithms (Clemmens et al., 2005), which has allowed significant advances on the engineering of canal control and automation.

Canal control algorithms can be heuristic, classical, predictive, or optimal (Clemmens and Schuurmans, 2004a). The most recent studies have returned to classical algorithms of the Proportional-Integral (PI) type, using new techniques for tuning the gains of the algorithms (Clemmens and Schuurmans, 2004b; Overloop et al., 2005; Guenova et al., 2005; Litrico et al., 2005; Piao and Burt, 2005). Their robustness, accuracy and easiness to implement on the field have favoured this new trend. However, there is not single solution or recipe applicable to all problems (Burt and Piao, 2004).

The goals of this study are: 1) to calibrate and validate a hydraulic model that allows simulation of the actual operation and resulting water flow regime in a real canal, and 2) the simulation and evaluation of alternative automatic control methods that may help to shift the operation of irrigation canals in Spain from supply-oriented to demand-oriented operation.

For the study, we chose the hydraulic model Simulation Irrigation Canal (SIC) (Malaterre and Baume, 1999) and a representative canal of the irrigation districts in Southern Spain as a case study.

MATERIAL AND METHODS

Description of the Study Canal

The case study involves Canal B in the Irrigation District “Sector BXII del Bajo Guadalquivir”, located in Lebrija, province of Seville, Spain (Figure 1). This is a branch canal 7.8 km long, with a bottom slope of 0.0002 and a trapezoidal cross section. It consists of four pools separated by check sluice gates (Figure 2). In the transition between of the pools, the trapezoidal cross sections become rectangular. Also, the first 89 m of the first pool is rectangular with a bottom slope of 0.00058. An inverted siphon is located in the fourth pool to cross a drainage ditch.

Pumping stations located just upstream the gates (labeled PS in Figure 2) deliver the irrigation water to the farms through pressurized pipe networks. The design flow for the canal pools are 5.4, 4.5, 3.35, and 1.98 m^3/s, respectively.

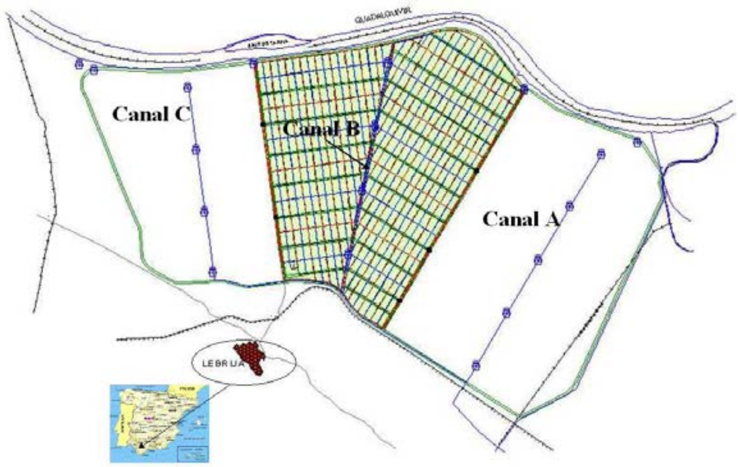


Figure 1. Localization of Canal B of the "Sector BXII del Bajo Guadalquivir"

The canal geometry was established with great detail using an electronic total station (GTS-210, TOPCON).

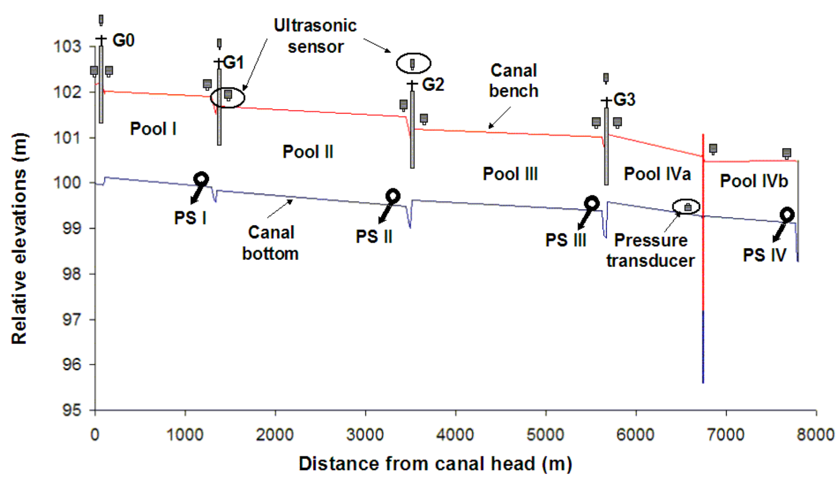


Figure 2. Longitudinal Sketch of Canal B of the "Sector BXII del Bajo Guadalquivir"

Water levels upstream and downstream of each check gate and downstream of the inverted siphon were measured by means of ultrasonic sensors; water level upstream the inverted siphon was measured with a pressure transducer. Gates openings were measured using ultrasonic sensors. All the information was recorded in data loggers.

Description of the Hydraulic Model (SIC)

SIC (Malaterre and Baume, 1999), the hydraulic model used in this study, simulates the water dynamics in canals based on the well known Saint-Venant equations. These equations are nonlinear hyperbolic partial differential equations dealing with the mass and momentum conservation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (1)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial Q^2/A}{\partial x}+gA\frac{\partial Z}{\partial x}=gA(i-J) \qquad (2)$$

where x (m) and t (s) are the distance and time dimensions, respectively, A (m^2) is the area of the flow cross section, Q (m^3/s) is the discharge, Z (m) is the elevation of the water surface, i (m/m) is the canal bottom slope, g (m/s^2) is the acceleration due to gravity, and J (m/m) is the friction slope. J is calculated in SIC based on Manning's formula.

Two boundary conditions are necessary for solving this system of differential equations. Typically, $Q(0,t) = Q_0(t)$ is the upstream boundary condition, where $Q_0(t)$ is a known inflow hydrograph and $Q(L,t)=Q_L(t)$ is the downstream boundary condition, with L the length of the canal and $Q_L(t)$ the discharge hydrograph at the canal tail (usually determined using a discharge equation function of the water level at $x = L$). The initial condition is given by the water level profile at $t = 0$: $Z(x,0)$.

Equations (1) and (2) are not valid to model water flow across hydraulic structures. Therefore, in the case of gates we resort to discharge equations of the form $Q = Q(Z_{us}, Z_{ds},W)$, with Z_{us} (m) and Z_{ds} (m) the water surface elevations upstream and downstream the gates, respectively, and W (m^2) the area of the flow cross section under the gates. In the case of a weir, the general form of the discharge equation is $Q = Q(Z_{us})$, with Z_{us} referred to the weir crest (Malaterre and Baume, 1999).

In SIC, equations (1) and (2) are linearized and discretized in time (Δt, time step) and space (Δx, space step) using the Preissmann implicit scheme (Cunge et al., 1980).

Control Logics

The main purpose of the canal control is matching the water supply with the water demand at the canal offtakes. Basically, there are two canal control logics (Burt, 1987; Buyalski et al., 1991): upstream control (Figure 3a) and downstream control (Figures 3b and 3c), each referring to the location of where information is needed by the control logic; downstream control is also called distant or local, respectively, when the sensor is located at the downstream section or the upstream section of the canal pool.

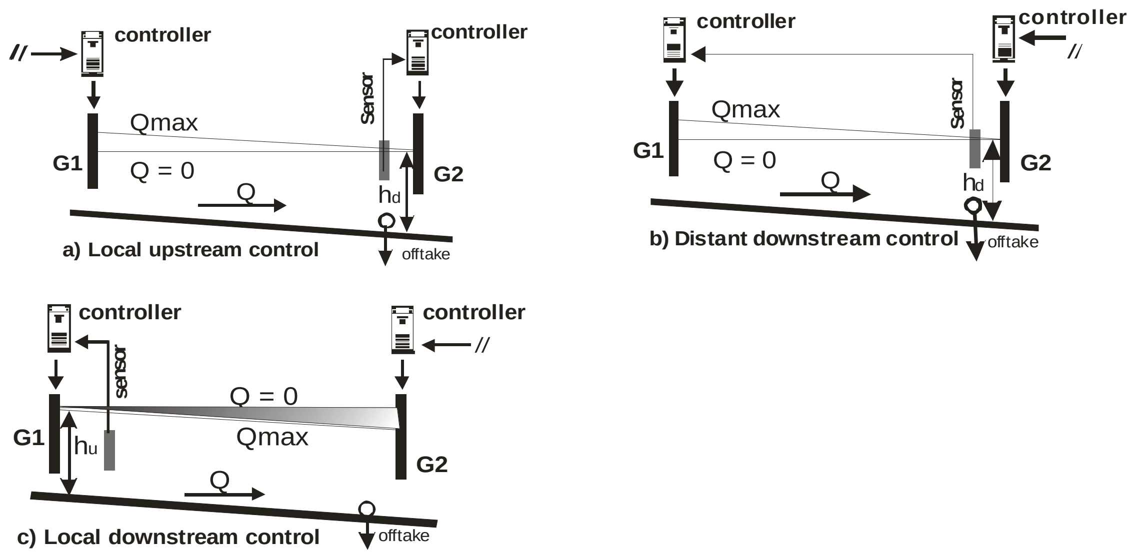


Figure 3. Canal Control Modes (Rijo and Arranja, 2005)

For local upstream control and distant downstream control, the water depth at the downstream end of each canal pool is the controlled variable and the control goal is to guarantee its fast convergence to a predefined set point. These are the two most commonly used control methods because with them, especially the first one, canals can be sized to convey the maximum flow and water depths in steady flow conditions never exceed the normal depth for the design flow (Rijo and Arranja, 2005). As it is shown in Figures 3a and 3b, the water surface profile pivots around the established downstream set point (h_d). A storage wedge is created between different steady-state flows profiles (Figures 3a and 3b represent the surface profiles for maximum and null flow). When the flow changes, the water surface and the storage volume within the pool changes in the same way (increasing or decreasing).

Calibration, Validation, and Application of SIC to the Study Canal

First, we calibrated discharge coefficients for each gate of the canal using a discharge equation of the type mentioned above:

$$Q = C_d W \sqrt{2g(Z_{us} - Z_{ds})} \quad (3)$$

where all the variables have been defined above except C_d, that is the discharge coefficient. C_d showed variations from gate to gate and in some cases also varied with the gate opening. For the purpose of the simulation with SIC, we used mean adjusted discharge coefficients: 0.87 for G0, 0.70 for G1, 0.66 for G2 and 0.64 for G3. The analysis of the variations of the discharge coefficients and of the errors in the determination of discharges will be the subject of a separate study.

The calibration and validation of SIC under unsteady flow conditions would require knowing the hydrographs at the offtakes. Unfortunately, this information was not available at the time of this evaluation. However, we considered that the Manning's roughness coefficient *n*, the parameter to be calibrated, would be rather similar under unsteady and steady regimes. Therefore, for calibrating *n*, we selected along the 2005 irrigation season 35 days and corresponding periods of steady state conditions (during which the outflows in the canal could be calculated by difference between the discharges under consecutive gates) with similar canal flow, and we did this calibration for each pool. Then SIC, using the flow and water levels measured in each pool, calculated *n*. We observed variations of *n* along the irrigation season, mainly due to the development of algae during springtime. The analysis of this variation of *n* and its effect on the outputs of the model and control gains will be matter of a separate article. Herein we will use the average *n* resulting of the *n* values obtained for the 35 steady state regimes used for the calibration. These average values were 0.016, 0.019, 0.019, and 0.022 for the first four canal pools, respectively.

Next, we proceeded to the validation of SIC. For this purpose, we used data sets independent of that used for the model calibration. As in the case of the calibration, we had to restrict the validation to steady state conditions, but we did so in two conditions. First, we validated the simulated water levels and gate openings by comparing the field measurements with the model outputs in 7 steady state regimes corresponding to 7 days along the 2005 irrigation season, with canal inflow varying from 1.82 to 3.2 m^3/s. Second, we simulated 2 steady regimes observed in the canal, entering in the model the actual inflow hydrograph, the actual gate movements, and outflows at the offtakes (estimated by difference between flows in consecutive gates). Third, we continued simulation until reaching a new steady regime. Finally, we compared the resulting water levels with those observed in the canal under the new steady conditions.

Once the model was validated, we proceeded to evaluate two automatic control methods: distant downstream (Figure 3b) and local upstream (3a). We fixed the outflow at offtakes PSI (0.597 m^3/s), PSII (0.686 m^3/s) and PSIII (0.717 m^3/s), and we increased instantaneously by 25% and decreased instantaneously by 50% a typical outflow at PSIV (1.2 $m^3\ s^{-1}$). For the distant downstream method this resulted in two tests: DSdistant-In and DSdistant-De, respectively. For the local upstream method, we tested six hypothetical operations of gate G0, three concerning the outflow increase at PSIV, and the other three concerning the decrease of outflow at PSIV:

- USlocal-In1, the operator increased inflow at G0 the same amount of the outflow increased at PSIV at the same time that the variation occurred at PSIV;
- USlocal-In2, as in the first test, but increasing during one hour the inflow at G0 an amount 150% of the outflow increase at PSIV in the same instant;
- USlocal-In3, as in test 2, but delaying the increase of flow at G0 75 minutes with respect to the time of variation at PSIV;
- USlocal-De1, as USlocal-In1 but decreasing the outflow at G0;
- USlocal-De2, as USlocal-In2 but decreasing the outflow at G0;
- USlocal-De3, as USlocal-In3 but decreasing the outflow at G0.

Then, for both control methods and all tests, we observed the resulting inflow hydrograph, gate G3 movement, water level and spills at the canal tail.

Control Algorithm. PI Controllers Tuning

In this study, we have used the Proportional-Integral (PI) control algorithm, a simplification of the Proportional, Integral and Derivative algorithm (PID) better adapted to canal control (Åström and Hagglund, 1995). This advantage has lead to many implementations of PI algorithms, as reported in recent publications (Clemmens and Schuurmans, 2004b; Piao and Burt, 2005; Litrico et al., 2005).

The PI algorithm can be written as:

$$U(t) = K_p \cdot e(t) + K_i \int e dt \qquad (4)$$

where $U(t)$ is the control action (gate opening in this case), $e(t)$ is the error or deviation of the controlled variable (water level in this case) from its target value at time t, and K_p and K_i are the proportional and integral gains, respectively.

In irrigation canals, oscillations and large deviations of the water levels from the target values and frequent variations of gate opening are undesirable. Thus, the performance criterion used herein was based on the integral of the water level errors and the integral of the gate opening variations (Baume et al., 1999). Therefore, optimal values of K_p and K_i were found by minimizing the function:

$$\xi = \sum_{i=1}^{n} \int_0^T \left[\left| Z_i(t) - Zr_i \right| + \delta w_i \right] \cdot dt \qquad (5)$$

where T (s) is the duration of the optimization period, Z_i (m) and Zr_i (m) are the measured and target water levels at pool i, respectively, and δw (m) is the gate opening variation. Function ξ (equation 5) was minimized using the simplex method (Nelder and Mead, 1965), the optimization algorithm implemented in SIC (Malaterre and Baume, 1999).

The resulting adjusted values of K_p and K_i are in Table 1.

Table 1. Optimized Controllers Gains

Gate	**Local upstream control**		**Distant downstream control**	
	K_p (-)	**K_i (s)**	**K_p (-)**	**K_i (s)**
G0			3.33	66.6
G1	-2.29	-803.5	4.50	23.3
G2	-3.14	-336.2	3.84	7.1
G3	-2.12	-716.2	2.20	2.6

RESULTS

Model Validation

Figure 4a compares measured and simulated water level values upstream and downstream check gates G0, G1, G2 and G3, inverted siphon, and at the end of the canal, for the selected seven independent steady state periods. The agreement is excellent. Also, the observed and measured gate openings (Figure 4b) agreed very well.

Considering two observed and validated initial steady-states, Figure 5 shows the water levels of the two correspondent final steady states, achieved after unsteady flow regimes. As shown, also in these cases the measured and simulated water levels agreed very well.

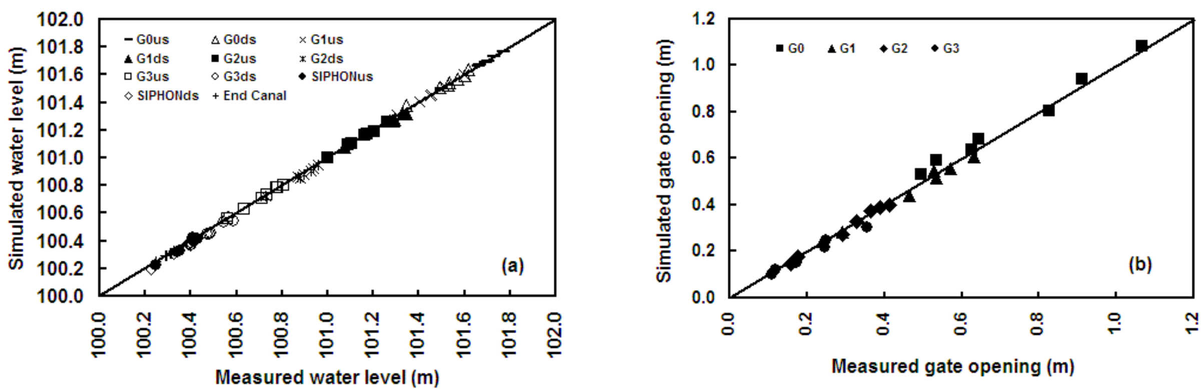


Figure 4. Measured and Simulated Values for Seven Independent Steady Flow Periods: a) Water Levels; b) Gate Openings.

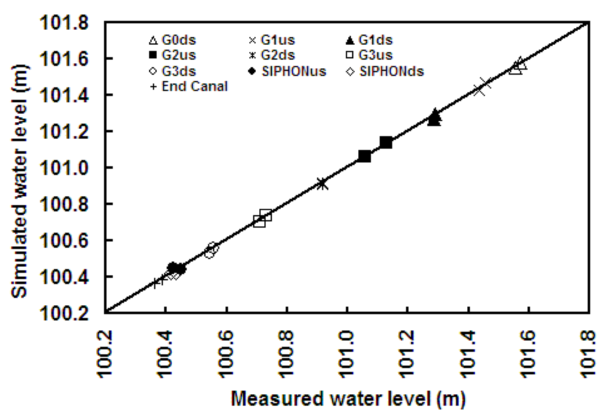


Figure 5. Measured and Simulated Water Levels for Two Real Steady Flow, Achieved After Unsteady Flow Periods.

In view of these results and despite the impossibility of validate the model under unsteady state conditions, we considered that the model had been sufficiently tested and validated to proceed to explore (under unsteady state conditions) with SIC alternative control methods in the study canal.

Control Simulation Results

Figures 6 and 7 show the simulation results for the irrigation canal under study, using the two implemented and tuned PI controllers, the local upstream and the distant downstream controllers.

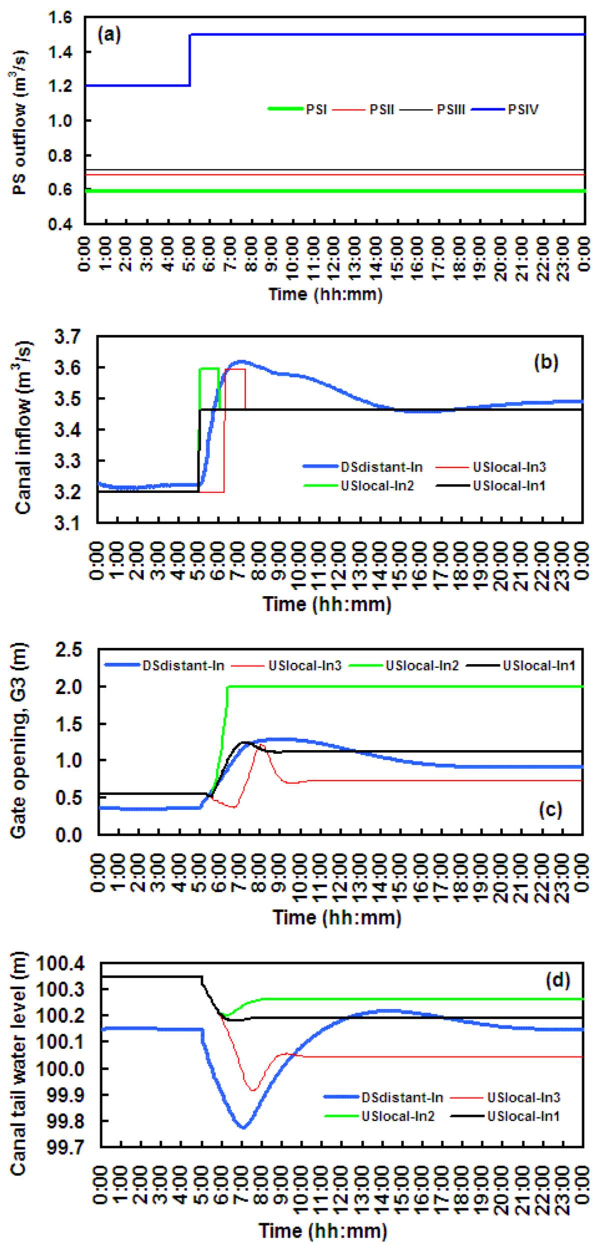


Figure 6. Local Upstream and Distant Downstream Controllers Responses to an Unexpected Outflow Increment at the Pumping Station PSIV. (a) Pumping Station Outflow,(b) Canal Inflow, (c) G3 Gate Opening, (d) Canal Tail Water Level

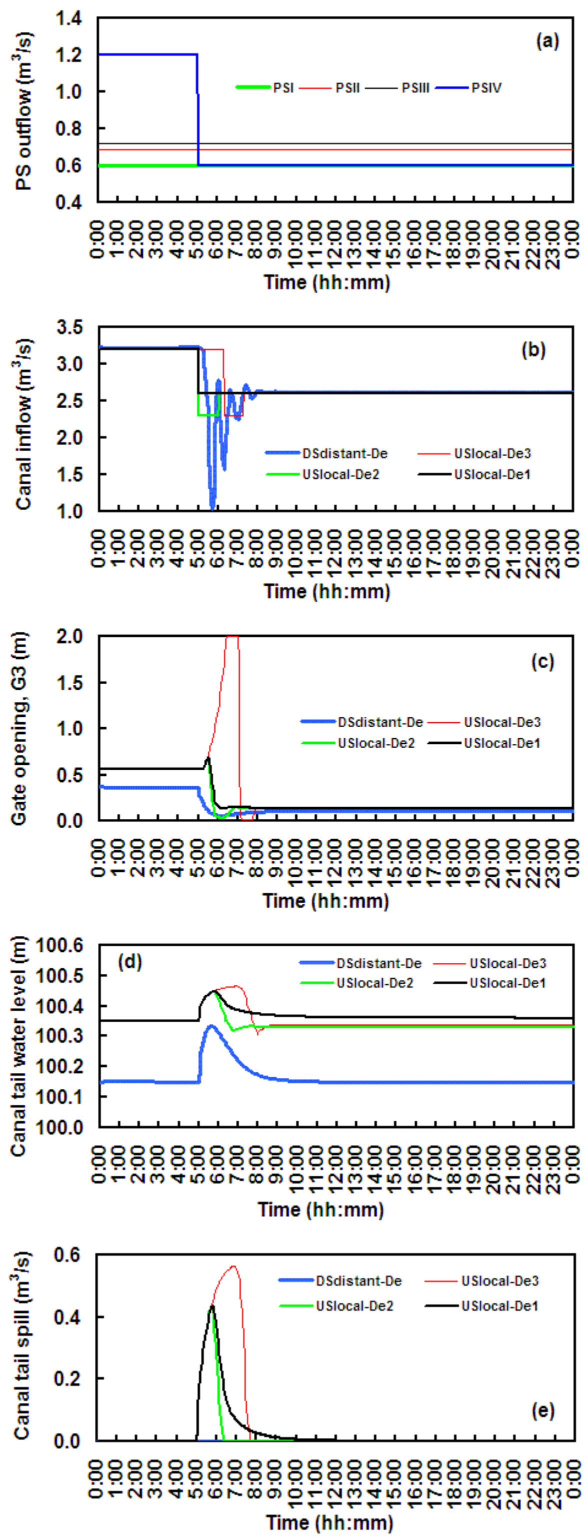


Figure 7. Local Upstream and Distant Downstream Controllers Responses to an Unexpected Outflow Decrement at the Pumping Station PSIV. (a) Pumping Station Outflow,(b) Canal Inflow, (c) G3 Gate Opening, (d) Canal Tail Water Level, (e) Canal Tail spill.

Figure 6 presents the response of the canal, under the operation of the two controllers, to the unexpected outflow increment at PSIV (from 1.2 m^3/s to 1.5 m^3/s) represented in Figure 6a; and Figure 7 presents that response to the unexpected outflow decrement (from 1.2 m^3/s to 0.6 m^3/s) at the same pumping station (Figure 7a). As stated under Calibration, Validation, and Application of SIC to the Study Canal (and shown in Figures 6a and 7a), the outflows for the other pumping stations (PSI, PSII, PSIII) remained constant for both scenarios.

Usually, the local upstream control guarantees an automatic water level control inside the canal, but it needs a complementary manual flow control at the canal intake (Rijo and Arranja, 2005). The canal intake is always operated according to the experience and personal judgements of the canal manager, which is one of the disadvantages of upstream control. For this reason, spills are common, especially when there is a demand-oriented operation. This situation is simulated here considering three attempts presented in Figures 6 and 7.

Figure 6b presents the canal inflow variations (USlocal-In1, USlocal-In2, USlocal-In3) imposed by the canal manager under upstream local control in order to adjust the canal dynamics to the unexpected increment of water demand. For the three attempts, the PSIV outflow increment was satisfied, with no spills at the canal end; but, as shown in Figure 6d, using a part of the water volume inside the canal pool IV. In other words, the water level did not return to the initial value for any of the three attempts. Moreover, Figure 6c shows that the controller stabilized the position of gate G3, but also shows that, for the USlocal-In2 attempt, gate G3 reached its maximum opening (2.0 m).

On the other hand, the distant downstream control response of the canal was better than that of the local upstream control. Now, the inflow canal hydrograph is a control output, the entire canal operates totally automatic (Rijo and Arranja, 2005), the gates operation is stable (Figure 6c), and the canal pool IV water level returns to its target value in a very stable way (Figure 6d).

Regarding the second group of scenarios (those considering outflow decrements at PSIV), Figure 7b presents attempts of manual regulation of the canal inflow similar to those presented in Figure 6b for the local upstream control, but now for the outflow decrement. The controlled water level inside canal pool IV is quickly regained, but the spills at the canal end became important for the three attempts. The excess of water inside the canal is well illustrated in Figure 7c for the USlocal-De 3, where it is shown that, during nearly one hour, gate G3 was completely open.

Also for the unexpected outflow decrement the canal responded to the distant downstream control mode better than to the local upstream control. The gates operation is stable (Figure 7c), the controlled water level regained its target value, and there are no spills at the canal end.

Both controllers guarantee a fast and stable response to the flow variations. The time for the control water depth to converge to the setpoints almost immediately (less than 1cm of water level error) for the local upstream controller and about 2 hours for the distant downstream controller.

SUMMARY

Considering a demand-oriented-canal operation, the main conclusion is that only the distant downstream control can quickly and automatically adjust the studied canal dynamics to unexpected water demands, with efficiency and no spills at the canal tail, even for sudden and significant flow variations. The tested automatic local upstream control improves the actual manual upstream control, saving labor in the canal operation, but only the distant downstream control guarantees a totally automatic canal operation. In the study case, with the last control mode, the actual number of seven canal managers could be reduced to only one, and the water delivery improved.

REFERENCES

Åström, K. J. and Hagglund, T.,. (1995). “PID controllers: theory, design and tuning,” 2nd ed. Instrument Society of America, Research Triangle Park, North Carolina.

Baume J.P., Malaterre P.O. and Sau J. (1999). “Tuning of PI controllers for an irrigation canal using optimization tools”. In Proc. of the USCID Workshop, 483-500, A.J. Clemmens & S.S. Anderson, eds. Phoenix, U.S.A.

Buyalski, C.P., Ehler, D.G., Falvey, H.T., Rogers, D.C. and Serfozo, E.A. (1991). “Canal systems automation manual. Vol I”, U.S.Department of the Interior, Bureau of Reclamation, Denver, E.U.A.

Burt, C. (1987). “Overview of canal control concepts” in ‘Planning, Operation, Rehabilitation and Automation of Irrigation Water Delivery systems’. ASCE. New York.

Burt, C.M. and Piao, X. (2004). "Advances in PLC-based irrigation canal automation". Irrigation and Drainage, 53, 29-37.

Clemmens A.J. (1987). “Delivery system schedules and required capacities”. In Planning, operation, rehabilitation and automation of irrigation water delivery systems, 18-34, ASCE, New-York.

Clemmens, A.J. and Schuurmans, J. (2004a). "Simple optimal downstream feedback canal controllers: theory". Journal of Irrigation and Drainage Engineering, 130(1), 26-34.

Clemmens, A.J. and Schuurmans, J. (2004b). "Simple optimal downstream feedback canal controllers: ASCE Test Case Results". Journal of Irrigation and Drainage Engineering, 130(1), 35-46.

Clemmens, A.J., Bautista, E., Wahlin, B.T. and Strand, R.J. (2005). “Simulation of automatic canal control systems.” Journal of Irrigation and Drainage Engineering, 131(4), 324-335.

Cunge, J.A., Holly, J.F.M. and Verwey, A. (1980). “Practical aspects of computational river hydraulics”. Pitman Publishing Limited, 420 p.

Guenova, I., Litrico, X., Fromion, V., Rijo, M. and Malaterre, P.O. (2005) “Stability analysis of classical decentralized control of irrigation canals”. 16th IFAC World Congress, Prague, July 4-8.

Kraatz, D.B. and Mahajan, I.K. (1975). “Small hydraulic structures”. Irrigation and Drainage Paper no. 26, FAO, Rome, Italy.

Litrico, X., Fromion, V., Baume, J.-P., Arranja, C. and Rijo, M. (2005). “Experimental validation of a methodology to control irrigation canals based on Saint-Venant equations”, Control Engineering Practice, 13/11, 1425-1437.

Malaterre, P.O. and Baume, J-P. (1999). “SIC 3.0, A simulation model for canal automation design”. CEMAGREF, Montpellier, France.

Nelder, J.A., and Mead, R. (1965). “A simplex method for function minimization”, Computer journal, 7, 308-313.

Overloop, van P.J., Schuurmans, J., Brouwer, R. and Burt, C.M. (2005). “Multiple-model optimization of proportional integral controllers on canals”. Journal of Irrigation and Drainage Engineering, (131)2, 190-196.

Piao, X. and Burt, C.M. (2005). “Tuning algorithms for automated canal control.” ITRC Report No. R05-005. September 2005.

Rijo, M. and Arranja, C. (2005). "Hydraulic performance of a downstream controlled irrigation canal equipped with different offtakes types". Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Vol II. March.

Shand, M.J. (1971). “Automatic downstream control systems for irrigation canals.” PhD thesis, University of California, Berkeley, CA.

HYDRODYNAMIC BEHAVIOR OF A CANAL NETWORK UNDER SIMULTANEOUS SUPPLY AND DEMAND BASED OPERATIONS

Sarfraz Munir[1]
Bart Schultz[2]
Abdul Hakeem Khan[3]
F.X. Suryadi[4]
Francis Gichuki[5]

ABSTRACT

The irrigation network of this study consists of three branch canals (the Machai Branch Canal, the Pehure High Level Canal (PHLC) and the Maira Branch Canal) connected to each other in such a way that the Machai Branch and the PHLC feed the Maira Branch Canal for providing a reliable irrigation service. The Machai Branch Canal has limited and erratic discharges and can not fulfill the peak water requirements of the Maira Branch Canal and therefore any deficiency in the supplies to the Maira Branch Canal is automatically compensated by the PHLC. PHLC is an automatic canal and has been equipped with Proportional Integral Derivative (PID) discharge controllers at its head whereas the Machai Branch Canal has fixed supply based operations. The Maira Branch Canal is also an automatically downstream controlled irrigation canal, which is operated according to crop water requirements using Crop Based Irrigation Operations (CBIO) model. Under this scheme of operations the flows remain changing most of the time following the crop water requirements curve. The frequent changes in discharges keep the canal in unsteady state conditions, which affect the functioning of automatic discharge and water level regulation structures. Efficient system operation is a prerequisite for getting better water productivity and the precise understanding of the behavior of the structures and canal's hydrodynamics against such changes is a key for getting effective system operations. In this paper the canal's hydrodynamic behavior and the automatic structures' functioning have been assessed and suggestions have been provided to fine tune the automatic discharge controllers in order to avoid the oscillatory and abrupt hydrodynamic behavior in the canal. The guidelines have been provided for the operation of the secondary system for achieving smooth and sustainable operations of the canals. In addition to this the effects of any discharge variation in the Machai Branch Canal on the automatic discharge controller's behavior also has been assessed.

[1] PhD Student, Water Engineering – Land and Water Development, UNESCO-IHE, Westvest 7, 2601 DA, Delft, the Netherlands, Phone: +31 15 2152 374, Fax: +31 15 2122 921, e-mail. s.munir@cgiar.org
[2] Professor of Land and Water Development, UNESCO-IHE, Delft, the Netherlands, Top advisor, Rijkswaterstaat, Utrecht, the Netherlands, e-mail. b.schultz@unesco-ihe.org
[3] Head IWMI-Pakistan, International Water Management Institute, Lahore, Pakistan, Phone: +92 42 5410050, e-mail: a.khan@cgiar.org
[4] Senior Lecturer, Land and Water Development, UNESCO-IHE, Delft, the Netherlands
[5] Principal Researcher, IWMI-Colombo, Sir Lanka. E-mail: f.gichuki@cgiar.org

INTRODUCTION

The irrigation system of Pakistan was designed about a century ago with the philosophy of protective irrigation, for spreading less water to vast agricultural lands for producing food to avoid the risk of famine. But with the passage of time parts of the irrigation system deteriorated because of inadequate operation and maintenance conditions, which resulted in low water productivity. On the other hand the region's population escalated so high that the population, which was only thirty million in 1947, touched the figure of 160 million in 2005. The food and fiber requirements soared so high that the granary of the old times became unable to feed such a large number of people.

Irrigation plays a crucial role in the agricultural sector of the country as seventy percent of the agricultural produce is from irrigated agriculture. The Indus Basin Irrigation System of the Pakistan is one the world's largest contiguous river flow irrigation system, consisting of most of the canal commands based on the protective irrigation philosophy. In the early nineties the government enhanced the water allowance of some of some of the canal commands in North-Western Frontier Province (NWFP) and increased it to 0.7 l/s/ha from the conventional 0.28 l/s/ha for getting higher cropping intensity and productivity. Now in Pakistan there are four canals having higher water allowance and are considered to be designed under productive irrigation concept (Helsima, 2002).

High water allowances improve water availability and cause agronomic benefits but also cause some ill effects like waterlogging and wastage of water, if used injudiciously. High water availability typically leads the irrigator to apply more and more water, which results in waterlogging. This problem has been tackled by adopting CBIO under which the supplies to canal command area are made compatible with the crop water requirements. As crop water requirements vary throughout the growing season, as a result the supplies also vary accordingly under CBIO. Judicious system operations are the perquisite for getting maximum benefits from any irrigation scheme and the assessment of hydrodynamic behavior of the irrigation canals provides a tool for getting efficient system operations.

Rationale of the Study

This irrigation system is a combination of fixed supply based and flexible demand based operations. The supply-based system is fully manually controlled whereas the flexible demand based system is automatically controlled at main canal level and manually controlled at the secondary level. The question arises here is how the operation of the manually controlled irrigation system affects the hydrodynamics of the automatically controlled system. For example how the automatic discharge controllers respond to any change in the flow, how the amount of discharge variation (water used or refused) and the location of this change along the canal affect the stability and response times in the automatically controlled irrigation canal? The time elapsed in reaching the effect downstream and gaining new steady state conditions are important to know in a manually upstream controlled irrigation canal whereas the reaction from the automatic discharge controllers and the stability of the hydrodynamics of the automatically downstream controlled irrigation canals are important to know for attaining equitable, reliable and stable canal operations.

Objectives

The overall objective of the study is to develop guidelines on how the canal network can be operated to improve the performance of the water delivery and distribution system. To produce these guidelines we need to:

- fine tune the (Proportional Integral, PI) controller for achieving smooth, stable and quick behavior of the automatic discharge controller at the PHLC head;
- assess the effects of various options of Crop Based Irrigation Operations on the automatic hydraulic behavior and stability of the canal;
- assess the effects of changes in water supply from the Machai Branch Canal on the response of discharge controllers at the PHLC head.

METHODS AND MATERIALS

Description of the Study Area

The study area lies in the North West Frontier Province (NWFP) of Pakistan between longitude 72^{o} to 72.8^{o} East and 33.9^{o} to 34.1^{o} North with a cultivable command area (CCA) of 89,300 ha. It gets water from two water resources, the Swat River and the Indus River. There is no reservoir at the headworks at the Swat River whereas at the Indus River there is the Tarbela Reservoir. The water availability in the rivers depends upon the snow melting on the mountains and rainfall in the catchments therefore they have maximum discharges in summer, especially in the monsoon and minimum in winter. The overall climate of the area is semi-arid with an average annual rainfall of 600-920 mm, of which 60 % occurs in the monsoon. The mean minimum and maximum temperatures vary between $3.5\text{-}42.2^{o}$ C. The average relative humidity is 40-72%, and pan evaporation is 77-428 mm/month (WAPDA, 2002). Schematic layout of the area is shown in Figure 1.

Irrigation Infrastructure

The irrigation system consists of three branch canals Machai, Maira and PHLC (Pehure High Level Canal). The Machai Branch canal is located at the upstream end and gets water from the Swat River through Upper Swat Canal and the PHLC gets water from Indus River through the Tarbela Reservoir. PHLC falls into Machai Branch Canal at a confluence downstream of RD 242 at an abscissa of 74000 m at Machai Branch Canal. These canals feed their own secondary system and also supply water to the Maira Branch Canal. The design contributions to Maira Branch Canal are from Machai 14 m^3/sec and from PHLC 24 m^3/sec. These supplies are variable as the system has demand-based operations and maximum discharge capacity of the canal at the confluence is 32 m^3/s. Salient features of the irrigation canals are given in Table 1.

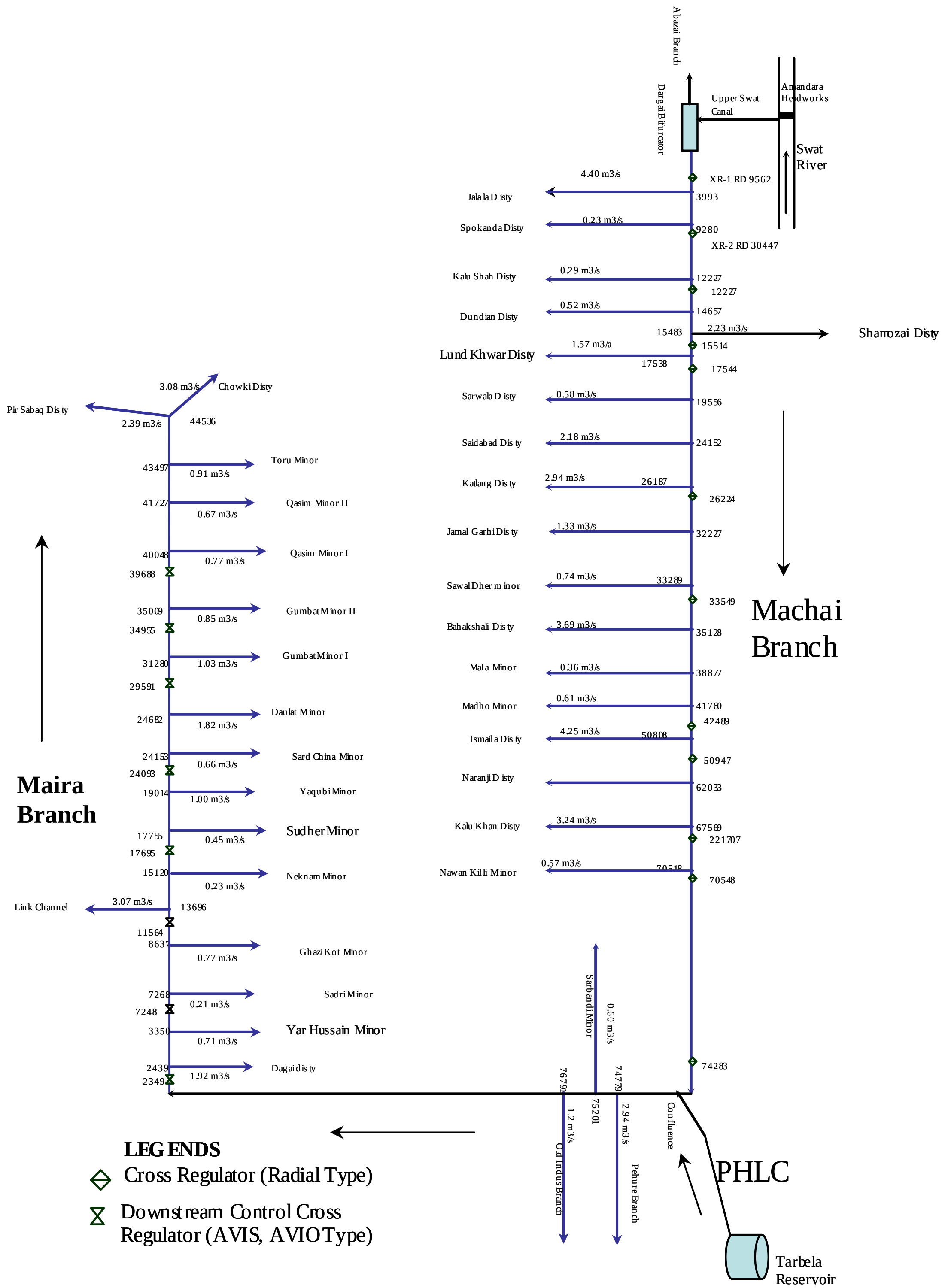


Figure 1. Schematic Map of the Study Area

Table 1. Salient Features of the Study Canals

S. No.	Description	Machai Branch Canal	Pehure High Level Canal	Lower Machai (d/s RD 242)	Maira Branch Canal
1	Discharge (m^3/s)	66.7	28.3	31.9	27.0
2	CCA (ha)	48,556	5,100	6,728	29,000
3	Length (km)	73.80	25.46	3.74	44.77
4	Cross regulators	12 No. Radial gates	03 No. AVIO, 02 No. AVIS		08 No. AVIS gates
5	Water level regulation	Manual	Automatic	Automatic	Automatic
6	Discharge control	Manual	Automatic	Automatic	Automatic
7	Secondary offtakes	21	5	3	17

System Operations

Operation Modes. The system has two modes of operations, fixed supply based operations (SBO) in the Machai Branch Canal and flexible demand based in the Maira Branch Canal and the PHLC.

Discharge and Water Level Controls. The supplies at the Machai Branch Canal head and water levels in the canal are manually controlled. In PHLC, the supplies at the head are controlled automatically at Gandaf Tunnel Outlet (GO) by automatic discharge controllers and water levels in the canal are controlled by automatically downstream controlled AVIS and AVIO cross regulators. The Gandaf Tunnel Outlet has been provided with a SCADA (Supervisory Control And Data Acquisition) system for automatic discharge control and monitoring, having PID based discharge controllers. Water levels in the main canal are controlled by AVIS and AVIO type cross regulators.

Secondary Offtakes Operations. The operation of the secondary system is manual in both the Machai and Maira Branch Canals and is automatic in PHLC except for one secondary offtake. In the Machai Branch Canal, the secondary offtakes are operated according to the water availability in the canal. In the Maira Branch Canal, the secondary offtakes are operated according the crop water requirements. The water use and refusal in the Machai Branch Canal depends upon water availability whereas in the Maira Branch Canal and the PHLC it depends upon crop water demands.

Crop Based Irrigation Operations (CBIO). It is a canal operations strategy in which the irrigation water supplies are made compatible with the command area crop water requirements (CWR). As the CWR are low in the beginning and end of the crop season and high in the middle, CBIO follows the same trend for supplying water. Less water is supplied during low requirements and maximum water is supplied during peak requirements. Lower Machai (downstream RD 242) and Maira Branch canal systems are operated according to CBIO. When the supplies fall below 80 % of the full supply discharge, a rotation system is introduced among the secondary offtakes. During very low crop water requirement periods the supplies are not reduced beyond a minimum of 50 % of the full supply discharge. These are the operational rules[6] of CBIO, which were envisaged during system design (Wisansawat & Pongput, 2000).

SCADA System. Supervisory Control And Data Acquisition (SCADA) is a real time discharge monitoring and control system, which collects the data on actual water levels and automatically controls the discharge supplies. A setpoint is established in the canal and any deficiency/excess to this setpoint is automatically adjusted, based on the choice of automatic discharge controller. In this system the setpoint is an absolute water level of 382.15 m above the mean sea level. A sensor has been installed one kilometer downstream and is connected electronically to the Master Control Panel (MCP), from where the control actions are taken according to the difference between target and actual water levels. The MCP is supported by a Hydraulic Power Pack to operate regulation valves. The discharge controllers in the SCADA system are the PID (Proportional Integral Derivative) controllers. A Human Machine Interface (HMI) has been provided to exchange information with the operator and to enter new desired values.

PID Controller. PID is an automatic discharge control algorithm, which compares the actual water level in the canal with the target water level and instructs the regulator (in this case the SCADA system) about the difference and action. The PID is a combination of P, PD or PI controllers. To understand the PID the definition of P, PD and PI controller is required which has been elaborated here. The P controller is the simplest continuous controller. Any deviation e at moment t actuates the regulator and is proportional to the difference e between measured water level and the setpoint (the target water level). The intensity of the controller reaction is given by the proportional gain factor, Kp. A low absolute value of Kp leads to damped gate reaction and a high value leads to a strong reaction of the regulator and may cause instability (Ankum, undated). The reaction from the P controller can be supported by applying a damping effect to the gate movement by D controller. The D-controller (Derivative controller) is added to the P-controller, to create a PD-controller. Its function is to anticipate the future behavior of the controlled variable (water level) by considering the rate of change. The D-controller avoids any rapid increase or decrease in the water levels caused by extra opening or closing of the gate. An I-controller always forces the water levels back to the setpoints. The integral gain factor, Ki, inserts a memory of deviations e of the past, by taking the sum of the all deviations up to the present time. Finally the PID is the combination of these three controllers for giving smooth and stable reactions to the deviations. It became available commercially in the 1930s. The first computer control applications in the process industries entered into the market in the early 1960s (Seborg et al. 1989).

Modeling Canal Operations

The assessment of hydrodynamic behavior of an irrigation canal network under varying flow conditions is a prerequisite for attaining efficient system operations. A computer model SIC (Simulation of Irrigation Canals) has been used to assess the hydrodynamics of the study canals. This is a 1-D hydrodynamic model which allows the simulation of irrigation canals under steady

---

[6] Operation Rule: The secondary offtakes can not be operated below 80% of design discharge and can not be kept closed for more than one week under CBIO in order to maintain equitable distribution of water and to avoid sedimentation in the secondary canals.

and unsteady state flow conditions (Cemagref, 2003). In steady state simulations it solves the differential equation of the water surface profile by numerical discretization. In unsteady state simulations it computes water surface profile in the canal by using Saint-Venant equations. These equations are solved by implicit finite difference discretization using Preissmann's scheme. In addition, the simulation model needs upstream and downstream boundary conditions as upstream discharge and downstream depth-discharge relationship.

Calibration of the Model. The model was calibrated by measuring water levels and discharges in the Maira Branch Canal. The canal was kept running for two to three days to obtain steady state conditions. Then the canal divided into three parts for the discharge and corresponding water level measurements and all of the inflows and outflows to and from these parts were measured. The resulting water levels were measured at the upstream and downstream of every cross regulator. The measured values were then compared with the simulated values of the discharges and water levels.

RESULTS AND DISCUSSIONS

CBIO Schedules

Figure 2 presents the crop water requirements of the area and the CBIO schedule for supplying irrigation water. In the CBIO schedule the crop water demands and supplies have been tried to match closely in order to control groundwater recharge and to minimize the water losses. The minimum flows have been provided fifty percent of the full supply discharge, when fifty percent of the offtakes remain closed for one week and the other fifty percent remain open. This rotation continues until the water requirements go higher than fifty percent. Then sixty seven percent offtakes are opened and if further demand increases then seventy five percent of the offtake are kept open. This rotation remains applicable until the crop water requirements go higher than the eighty percent of the design discharge. Then the system remains fully open until the crop water requirements fall below eighty percent again.

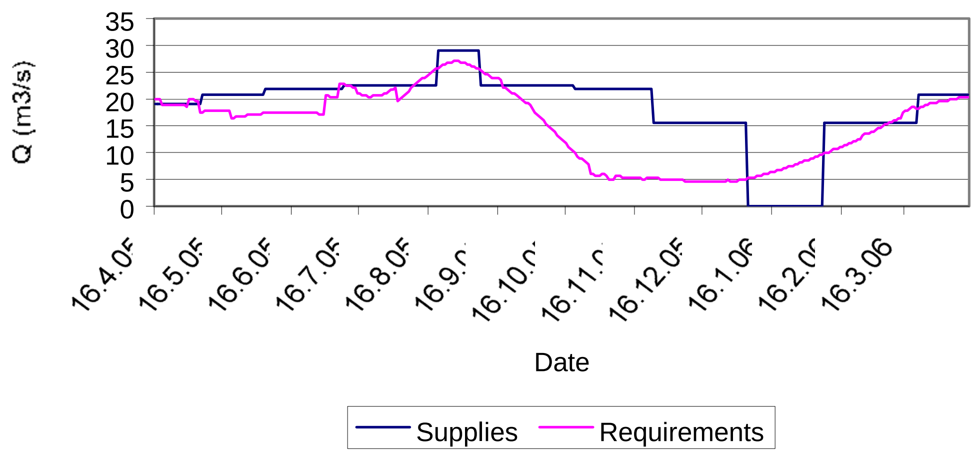


Figure 2. CBIO Schedule for the Year 2005-06

Calibration Results

The model was run according to the field conditions. The discharge withdrawn by the offtakes was imposed on these offtakes in the simulation, which resulted in good match even by having the design Manning roughness values. Figure 3 presents the measured and simulated water levels along the canal. The measured and simulated water levels are pretty close to each other.

The measured and simulated discharges were also compared along the canal. The discharge measurement took place at head, middle, and tail of the canal. This comparison shows that the measured and simulated values are fairly close to each other. The simulated and measured downstream water levels are almost same and the simulated upstream water levels are on average 0.12 m higher than the measured ones. The discharge comparison results are shown in Table 2.

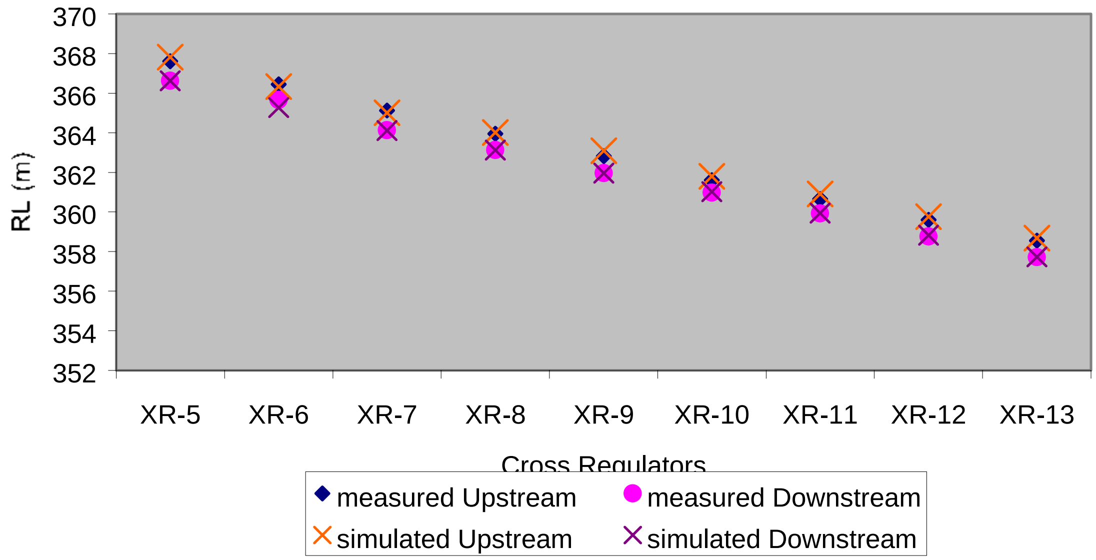


Figure 3. Water Levels (Simulated and Measured)

Table 2. Measured and Simulated Discharges along the Canal

S. No.	Location	Distance from Head Gate (m)	Q Measured (cumec)	Q Simulated (cumec)	% Difference
1	Head	500	18.01	17.56	2.50
2	Middle	16570	11.91	11.56	2.94
3	Tail	43220	6.55	5.99	8.55

Fine Tuning of PID Factors

The PID coefficients play a key role in water regulation in the continuous automatic flow control systems. The selection of correct values of the proportional, integral, and derivative gain factors leads to a safe and stable operations of the canal and prevents any oscillatory behavior of the automatically regulated hydromechanical gates. The quick response of the discharge regulator to the deviations from the setpoint (proportional property), the damping effect to these responses (derivative property), and finally meeting the setpoint (the integral property) are the characteristics of PID controllers. Various values of PI factors have been tested in order to find some optimum values for improving the hydrodynamic performance of the system in case of frequent changes in flow demand and supply.

Kp (Proportional Gain Factor) Values. Three different values of proportional gain factors have been tested as given in Table 3 along with other information on the refusal of the discharge and their location.

Table 3**.** Different Values of Kp and Other Parameters

S. No.	Kp value	Q from Machai	Q at PHLC Head	Q at Confluence	Q refused (% of Q @ confluence)	Location of closed offtakes
		m^3/s	m^3/s	m^3/s		
1	1.30	8.00	17.50	25.5	24%	Head
2	2.00	8.00	17.50	25.5	24%	Head
3	2.50	8.00	17.50	25.5	24%	Head

In Figure 4 the results of the simulations have been presented where the target water level is 382.15 m. An amount of 6.06 m^3/sec discharge was refused at the head of the Maria Branch Canal by closing five secondary offtakes. The discharge released under three different values of the Kp factor, as given in the Table 3, was tested and the effect was observed on the reactions from the Gandaf Tunnel Outlet (GO) and the results are shown in Figure 4.

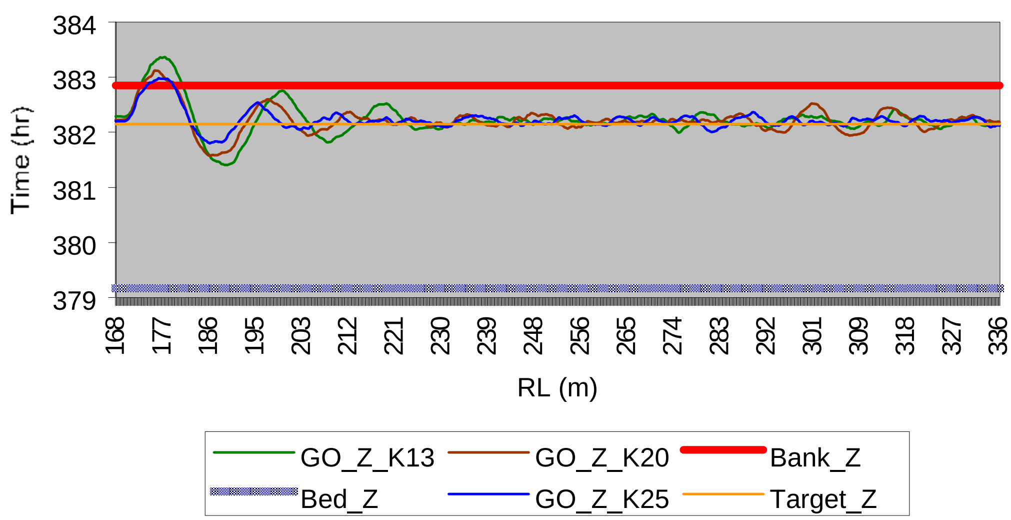


Figure 4**.** Water Level Oscillations Under Different Kp Values

Figure 4 shows that the Kp = 1.30, which is basically the same value used at the Gandaf Tunnel Outlet, gives oscillatory behavior and requires a long time to comeback into steady state conditions, whereas the Kp values 2.00 and 2.50 give comparatively less oscillations and the discharge gets stable earlier. The discharge released against these Kp values is shown in Figure 5, which also shows almost the same behavior. The discharge released under Kp = 1.30 becomes stable after about 64 hours, whereas it becomes stable under Kp = 2.00 and Kp = 2.50 after 46 hours. The maximum and minimum discharge released under all these Kp values is almost the same.

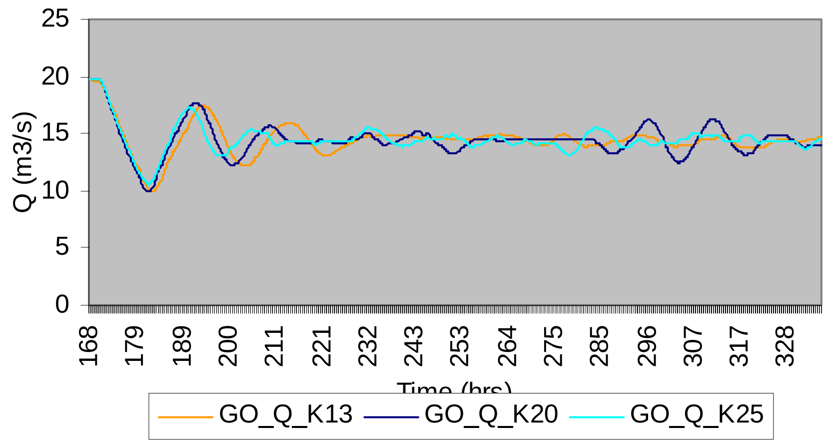


Figure 5**.** Discharge Released Under Different Kp Values

<u>Testing the Integral Time (Ti) Values .</u> The integral time, Ti, is another important parameter which affects the response of the PI controller. The integral property reduces the decrement and brings the deviations to zero. Two different values of integral time, Ti = 3000 seconds and 1200 seconds were simulated with the same amount of discharge. It has been tested that, which value brings the stability earlier in the system and reduces the oscillatory behavior. The results have been presented in the Figure 6. The flow parameters during this test were the same as given in the Table 3. Figure 6 shows that the Ti = 1200 s led smoothly but slowly to the new discharge conditions as compared to Ti = 3000 s, which though achieved new conditions earlier but did not get stability even after 250 hours after the downstream change in flow. The system was fully stable after 230 hours in case of the Ti = 12000. So Ti = 1200 s seems better option for smooth and stable canal operations.

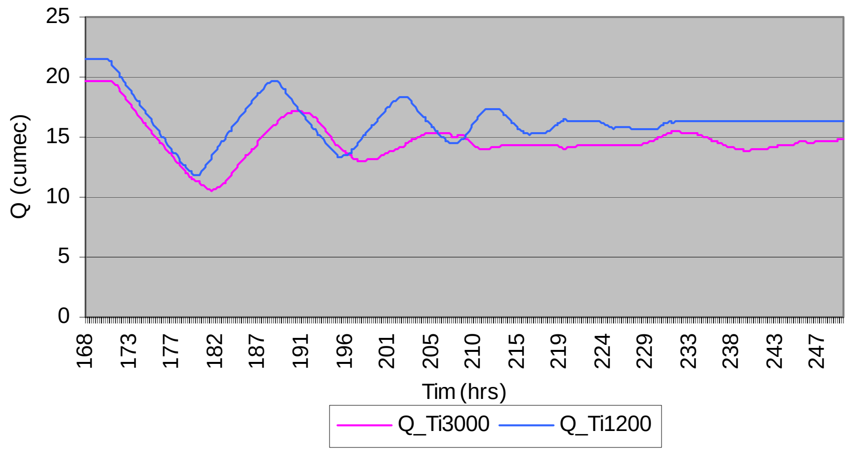


Figure 6. Discharge Variations Under Ti = 3000 s and 1200 s

Effect of Amount and Location of Discharge Refusal

Effect of Location of Discharge Refusal. In this scenario the effect of discharge refusal from different locations along the canal has been simulated to assess the response times and system stability against these water refusals. It has been observed after how long the system gets new steady state position. Basically the effect of distance on the response times has been assessed. The effect of the location of offtakes closed on the system stability has been compared and results have been presented in Figure 7. The offtakes were grouped with almost the same amount of discharge at the head portion, tail portion, and along the canal (composite) and their effects were simulated on the system behavior. Table 4 gives the information about the offtakes grouping, their location and their total discharge.

Table 4. Information on the Offtake Groupings

Group No.	Location	Total Discharge cumec	Percentage of Flow at Confluence	Offtakes names
1	Head	6.1	24	Pehur, Sarbandi, Old Indus, Dagi, Yar Hussain
2	Tail	6.1	24	Gumbat 2, Qasim 1 & 2, Toru, PirSabaq
3	Mixed	5.2	21	Pehur, Dagi, Yaqubi, Gumbat 2

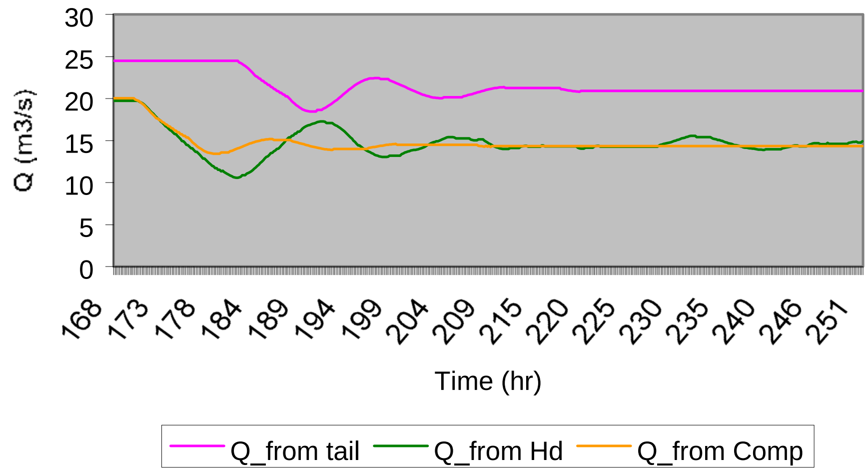


Figure 7. Flow Stability and Response Times of Offtake Closures at Different Locations

Figure 7 shows that the composite grouping of offtakes gives early stability and less oscillations as compared to the discharge refusal at head and tail. The discharge controller responds to discharge variations at the tail after 14 hours and becomes stable after 51 hours. Whereas the discharge controller at GO responds after 3 hours to discharge refusal at head and becomes stable after 51 hours. The discharge controller reacts after 3 hours to the discharge refusal along the canal (composite) and becomes stable after 29 hours. These results show that the mixed offtakes closing is a better option for stable system operations.

Effect of Amount of Discharge Refusal. The amount of discharge refusal also affects the stability of the system and response times. The effects of two different amounts of discharges were compared and the results have been presented in Figure 8, which shows that a high number of discharge refusal takes more time for system stability, whereas in limited discharge refusal situations the system stabilizes comparatively earlier. For the 50 percent discharge refusal the system took 48 hours to become stable whereas in case of discharge refusal of 24 percent the system became stable in 28 hours.

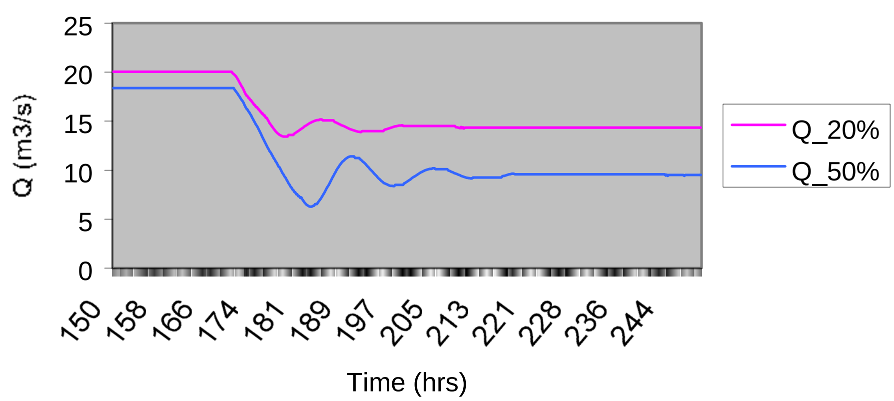


Figure 8. Response Times of Eighty Percent and Fifty Percent Offtake Closures along the Canal

Testing of the CBIO Schedules

The overall purpose of this paper is to describe the hydrodynamic behavior of the automatically downstream controlled system under the CBIO. To assess the hydrodynamic behavior of the canals and the system stability under these operations is very important from the point of view of efficient and reliable system operations. Hence four different options of CBIO were simulated and the results are presented in the Figure 9. The CBIO options tested were running the system on 100, 80, 67, and 50 percent of the design supply and then again on 100 percent.

Figure 9 shows that the gradual increase or decrease in flow conditions gets stability earlier and takes less response time, whereas the big changes in discharge refusal or discharge opening result in prolonged instability and longer response times as given in Table 5. It is clear from the Table 5 that as the amount of discharge variation increases or decreases the response increases and decreases accordingly.

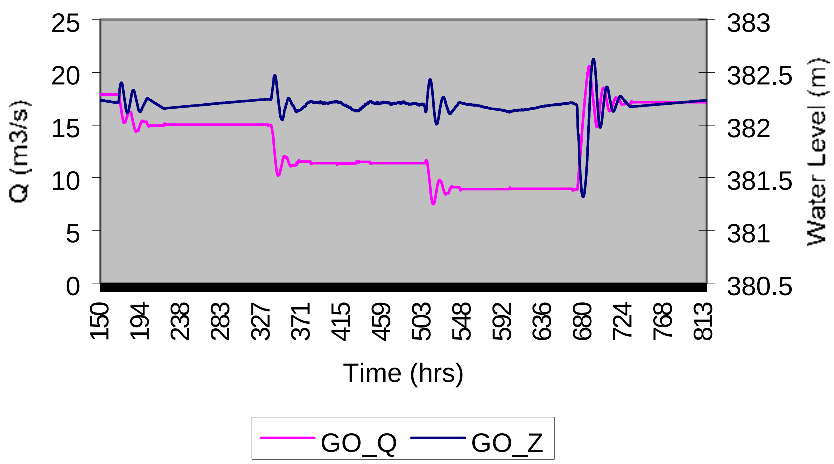


Figure 9. Testing of CBIO Schedule at 100, 80, 67, 50 and 100 % of Full Supply Discharge

Table 5. Response Times of Different Flow Changes

S. No	Flow variations (percentage)	Amount of Flow supplies at Confluence (m^3/s)	Response Time (hrs)
1	100 → 80	2.9	32.83
2	80 → 67	3.6	44.33
3	67 → 50	2.5	38.67
4	50 → 100	8.2	64.17

Gate Responses

Gate response to discharge variations is a very crucial factor for smooth and sustainable irrigation system operations. It needs to be assured that the frequent opening and closing of secondary offtakes due to changes in water demands in the canal may not lead to abrupt opening/closing or oscillations in the automatic water level control AVIO/AVIS gates of the cross regulators. Hence the AVIO/AVIS gates behavior under some discharge refusals have been tested and the results are presented in Figure 10. A discharge of 6 m^3/s was refused at the tail portion of the Maira Branch Canal. The discharge refusing point was selected at the tail portion so that the behavior of all the automatic cross regulators could be assessed. Figure 10 shows that the gates settled smoothly to the new positions within 3-6 hours.

Together with the smooth settling and opening of the gates, their reaction time is also important in order to estimate the time elapsed in traveling of the effect of change in the system to the controller. Table 6 gives the reaction times of the cross regulators from cross regulator No. 13 (XR-13) at Maira Branch Tail to cross regulator No. 1 (XR-1) at PHLC head, which finally conveys the messages of change to sensor and discharge control system. The total time elapsed in conveying the message of change from XR-13 to XR-1 is 10.67 hours and the final settlement takes place after 16.67 hours. Every next cross regulator took about 0.89 hours to respond and finally it settles on new position after 5.58 hours, on average, under the given conditions.

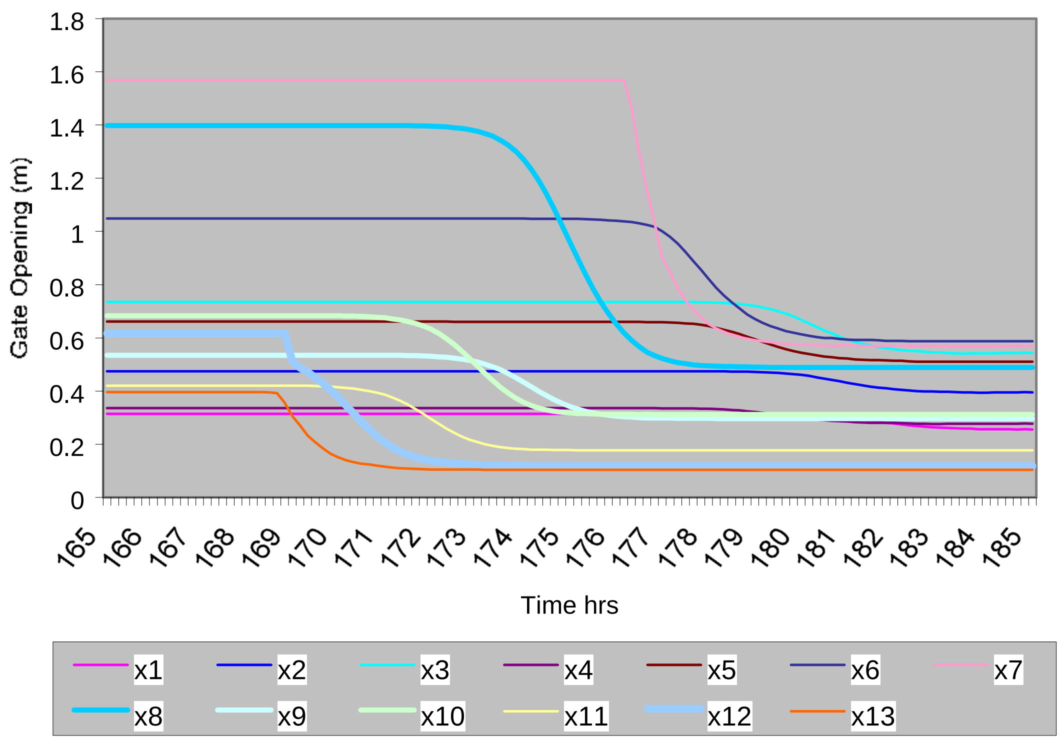


Figure 10**.** Gate Responses to Some Offtake Closures at the Tail of the Maira Branch Canal

Table 6**.** Gate Openings and Time Elapsed in Response of Discharge Refusal at Maira Tail

Cross Regulator	Distance from from PHLC Head	Start Time	End Time	Initial Opening	Final Opening
	M	hrs	Hrs	m	m
XR-13	67,124	168.33	171.83	0.396	0.106
XR-12	62,374	168.83	173.67	0.671	0.119
XR-11	57,024	169.33	175.00	0.420	0.178
XR-10	51,524	170.33	175.67	0.682	0.313
XR-9	45,124	171.33	177.17	0.543	0.312
XR-8	38,794	172.00	178.50	1.396	0.492
XR-7	34,674	176.17	180.50	1.596	0.572
XR-6	29,774	174.83	183.00	1.048	0.588
XR-5	24,254	176.50	182.33	0.660	0.512
XR-4	21,312	176.83	182.33	0.336	0.296
XR-3	15,032	177.67	183.67	0.734	0.542
XR-2	11,485	178.33	183.33	0.474	0.396
XR-1	4,487	179.00	185.00	0.322	0.255

Discharge Variations in Machai Branch Canal and Responses from PHLC (Gandaf Outlet)

According to the design concept of the combined USC (Upper Swat Canal)-PHLC system, PHLC is supposed to supplement the flows to the Machai Branch Canal for reliable irrigation water supply to the Maira Branch Canal. The water availability in the Machai Branch Canal depends upon the flow availability in the Swat River. As there is no storage reservoir at the headworks, the flow availability in the Machai Branch Canal is quite variable. Therefore, it becomes very important to assess the effect of different scenarios of water availability in the Machai Branch Canal on the automatic operation of the PHLC. Two scenarios have been tested with maximum and minimum supplies from the Machai Branch Canal. It has been tested how the automatic discharge controllers respond to any variation in Machai Branch Canal discharges. The lag times in the Machai Branch Canal also have been estimated and the time required by the PHLC to respond to these changes also has been assessed. The results of these simulations are presented in the Figure 11. A discharge of 10 m^3/s was increased at the Machai Branch head and in response of this the automatic flow adjustment started to take place at the Gandaf Outlet after 13.33 hours and finally it reached a new equilibrium after 98.67 hours.

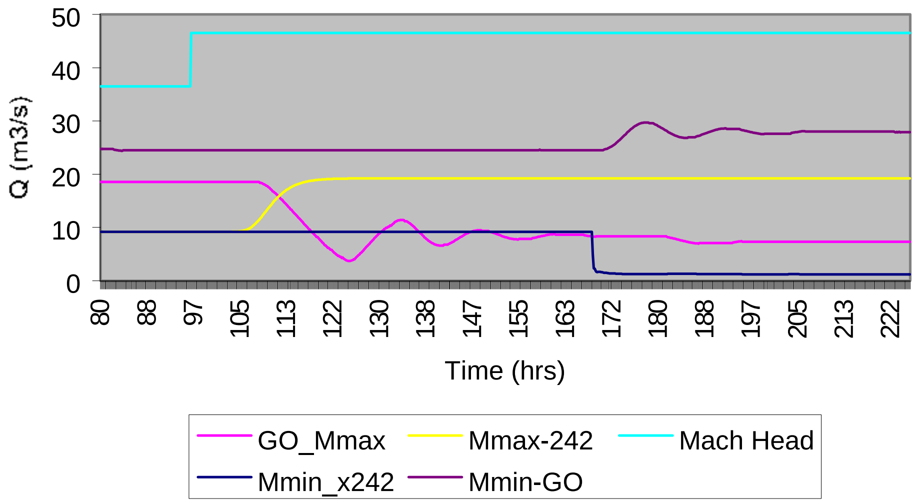


Figure 11**.** Gandaf Outlet's Behavior Against Variation in Machai Branch Canal

The time elapsed in reaching the effect of this change at the RD 242 (74 km), the last cross-regulator of the Machai Branch Canal, was 9.5 hours which reached a new steady state after 16 hours. Similarly the other scenario was tested by reducing the contribution from the Machai Branch Canal to the Maira Branch Canal. The automatic discharge controllers responded according to this deficiency in the flows and the same amount of discharge was increased automatically at Gandaf Outlet as shown in Figure 11.

CONCLUSIONS

A good proximity was found in the simulated and measured water levels and discharges in the Maira Branch Canal. The proportional gain and integral time of PI, Kp = 2.5 and Ki = 1200 seconds led to comparatively smooth and stable system operations. The composite closing of the offtakes resulted in less response times than the offtakes closed at the tail of the canal and in this case the canal achieved early stability. The amount of discharges refusal also affected the response time, in case of small amounts of discharge refusal by the secondary system, the main canal achieved new equilibrium conditions earlier and vice versa. Four different cycles of CBIO schedules were tested and found that the gradual increase or decrease in the discharge withdrawals favored smooth system operations and achieved new equilibrium conditions earlier as compared to the large variations in discharge. The hydro-mechanical cross regulators reacted to the water level changes and settled at new positions without any oscillations at the given amounts of discharges under the CBIO. On a refusal of 6 m^3/s discharge at the tail end of the Maira Branch Canal every consecutive cross regulator responded to these changes after 0.85 hours and the final settlement was made after 16.67 hours at the last cross regulator at the head portion of the PHLC. The Gandaf Outlet responded efficiently to the changes in contribution from the Machai Branch Canal. Any deficiency or addition of the discharges from the Machai Branch Canal to Lower Machai and Maira Branch Canal was accordingly adjusted by the Gandaf Outlet automatically. These simulations of various parameters show a stable hydrodynamic behavior of the canals and automatic discharge regulators. Following these parameters the operations of the system can be improved for having reliable irrigation water supplies.

REFERENCES

[1]Ankum. P. (Undated). Lecture notes on “Flow Control in Irrigation Systems”. UNESCO-IHE, the Netherlands

[2]Cemagref., (2003). SIC (Simulation of Irrigation Canals) User’s Gudie. The French institute of agricultural and environmental engineering research. Montpellier Cedex 1, France.

[3]Helsema, G. E. van. (2002). Trial & Re-Trial; The evolution of irrigation modernization in NWFP, Pakistan. PhD Thesis. Wageningen University, the Netherlands.

[4]Seborg E. E., T.F. Edgar and D. A. Mellicham. 1989. Process dynamics and control. Wiley series in chemical engineering. New York.

[5]WAPDA. 2002. “Operation and Maintenance Manual for USC - PHLC” Tarbela.

[6]Wisansawat, K., K. Pongput. 2000. “CBIO, Scheduling Model for Crop Based Irrigation Operations. User Manual and Technical Guide”.

SIMULATION ON THE EFFECT OF MICROTOPOGRAPHY SPATIAL VARIABILITY ON BASIN IRRIGATION PERFORMANCE

Mei Jian Bai[1]
Di Xu
Yi Nong Li

ABSTRACT

Studying the impact of microtopography on irrigation performance is important for improving the management of basin irrigation systems. However, the limitation of field experiments will restrict the studies on the impact of microtopography spatial variability on basin irrigation performance. Thus, firstly this paper analyzed the spatial variability characteristics of field-measured Surface Relative Elevations (SRE). The correlations between the field geometry parameters and the spatial variability characteristics of SRE were evaluated, and the estimation methods for parameters of the semi-variogram of SRE were determined. Secondly, a microtopography stochastic generating model was built up based on the Monte-Carlo and the Kriging interpolation techniques. Lastly, the effect of spatial variability of microtopography on the performance of basin irrigation was evaluated by using of the numerical simulation model. Results showed that the microtopography undulation degree and the spatial distribution difference of undulation location had obvious effect on the basin irrigation performance. The average irrigation depth (Z'_{avg}), corresponding to the water just cover the whole basin surface is increased while the irrigation application efficiency (E_a) and the irrigation uniformity (CU) is decreased when the field elevation non-uniformity, measured by the standard deviation of SRE (S_d) is increased. The effect of spatial distribution of undulation location on the irrigation performance was dependent upon the microtopography undulation degree, when S_d is less than 2cm the impacts can be neglected, while S_d is greater than 2cm, the influence should be considered.

INTRODUCTION

Basin microtopography is defined as the undulation of topography relative to the basin design surface. The spatial variability of microtopography includes the undulation degree and the spatial distribution of undulation location of the field elevations. Generally, the standard deviation (S_d) of Surface Relative Elevation (SRE) is used to evaluate the degree of undulation (Pereira, et al, 1996; Xu,et al 2002). However, for the same S_d the spatial distribution of undulation location of field elevations is not unique.

The spatial distribution of SRE significantly influences the water advance and recession process (Playan, et al, 1996a; Li,et al,2000). Therefore, studying the effect of the spatial variability of microtopography on the surface irrigation performance can provide guidance for surface

[1]National Center of Efficient Irrigation Engineering and Technology Research-Beijing; China Institute of Water Resources and Hydropower Research, 20 West Chegonzhuang Road 100044, Beijing, China. baimj@iwhr.com; xudi@iwhr.com; liyinong@iwhr.com

irrigation design and management. In past research, more attention was given to the undulation degree, but the discrepancy of spatial distribution of undulation location was completely neglected.

Because of the limitation of field-measured data, studies on effect of microtopography on irrigation performance based on a particular field data set can't be easily generalized. Clemmens, et al (1999) and Li, et al (2001b) both presented that the microtopography data was randomly generated using Monte-Carlo method based on the statistical characteristics of SRE, but those studies only considered that the value and the spatial distribution of SRE was stochastic, and thus any spatial structure was ignored. Previous studies have shown that the SRE are spatially correlated. (Playan, et al,1996a; Zapata, et al, 2000; Xu, et al, 2005).

This paper analyzed firslyt the spatial variability of SRE based on the field-measured data. The correlations between the field geometry parameters and the spatial variability characteristics of SRE were evaluated, and the estimation methods for parameters of the semi-variogram of SRE were determined. Secondly, microtopography stochastic generating model was built up with Monte-Carlo and Kriging interpolation techniques. Lastly, different microtopography conditions were produced by the model and the corresponding basin irrigation process was simulated using two dimensional irrigation simulation model B2D. The effect of spatial variability of microtopography on the basin irrigation performance was evaluated.

MATERIAL AND METHODS

Irrigation Performance Indicators

Many indicators are available to evaluate irrigation performance. In this paper the water application efficiency(E_a), the coefficient of uniformity(CU) and the average irrigation depth corresponding to the water justly cover the whole basin surface (Z'_{avg}) were selected. E_a and CU are defined as (Burt,et al,1997):

$$E_a = 100\frac{Z_r}{z_{AVG}} \tag{1}$$

$$CU = 1 - \frac{\sum_{i=1}^{n} \left| Z_i - Z_{avg} \right|}{n.Z_{avg}} \tag{2}$$

Where Z_r is the average depth of water added to the root zone, mm; Z_{avg} is the average depth of water applied to the field, mm; Z_i is the infiltrated depth at the observation point i; n is the number of observations.

Surface Irrigation Simulation Model Description

The two-dimensional irrigation simulation model B2D (Playan et al, 1994a, b) was adopted to simulate surface irrigation process in this study. This model solves the 2D hydrodynamic Saint Venant equations using an explicit finite-difference leapfrog scheme, and can handle spatially varied infiltration problem. Playan et al (1996b) extended the original model function by introducing the treatment of the spatial variability of soil surface elevation. This two-dimensional model provides a more realistic representation of the irrigation system than a one dimensional model in cases where field undulations perpendicular to the flow direction are large or where inflow is concentrated at point inlets instead of uniformly distributed along the upstream end of the field.

Geostatistics

The spatial variability of SRE was analyzed using geostatistical techniques. The experimental semivariogram $\gamma(h)$ was used to describe the spatial variogram,

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{N}\left[Z(x_i) - Z(x_i + h)\right]^2 \quad (3)$$

Where, x_i is the coordinate of observed point i; $Z(x_i)$ is elevation at x_i, cm; h is the distance between pairs of observations, m; N is the number of data pairs.

Theoretical semivariograms are functions used to model experimental data. These functions are based on three parameters: nugget, sill, and range. The nugget is the value of the semivariogram for a distance equal to zero. A nonzero nugget can be interpreted as an indication of a systematic measurement error or the existence of spatial variation at a smaller scale than measured. The final stable value of the semivariogram equals the sum of sill and nugget .The range is the distance at which the semivariance reaches its stable value.

The indicative goodness of fit (IGF) (Pannatier, 1996) was adopted to quantify the fit error between the experimental and theoretical semivariogram. The theoretical semivariogram of SRE was selected according to the principle of minimum difference.

SPATIAL VARIABILITY OF SRE

Basic Data

The field-measured data of SRE of 116 typical basins from Daxing and Changping in Beijing, Xiongxian in Hebei Province and Bojili in Shandong Province were analyzed. All typical basins were classified into three types by geometry parameters (Table.1), which basically included all the geometry characteristic of basins in different irrigation districts of North China. The SRE of all typical basins was observed by level or GPS with the range of observation space 1.5m-10m.

Table 1.The Statistical Characteristics of Geometry Parameters for each Type of Basin

Geometry parameters	strip basin, (length/width>3 ,width≤10m)		narrow basin (length/width>3,width>10m)		wide basin (length/width<3)	
	range	mean	range	mean	range	mean
Length /m	30~278	84	50~300	158	20~200	93
Width /m	1.9~10.0	4.9	10.0~35.0	19.0	10.0~80.0	51.0
Area /hm^2	0.01~0.17	0.04	0.05~0.93	0.33	0.02~1.60	0.60
Slope /‰	0.1~4.3	1.0	0.0~3.6	0.9	0.0~3.3	1.1

The probability distribution of SRE of 116 basins was tested by one-sample K-S test (Yu, 2003).Table.2 presents the statistical of Asymp.Sig (2-tailed) for different basin types. Results show that the SRE of all typical basins meet the normal distribution at the 0.05 probability level.

Table 2. The Statistical of Asymp.Sig (2-tailed) of K-S test for each Type of Basin

basin type	maximum /%	minimum /%	mean /%
strip basin	98	25	68
narrow basin	96	38	65
wide basin	92	35	57

Spatial Variability Structure of SRE

The experimental and theoretical semivariograms of SRE for different IGF are presented in Figure 1. When IGF is small, the fitting error between experimental and theoretical semivariograms is small for different lag distances. However, when IGF is large, the fitting error mainly occurs at a large lag distance. Because the observation data at a large lag distance mainly delegate the spatial structure of sample at the edge of plot, which is not the main spatial structure of sample (Burrough, 1991). Therefore more attentions are paid to the fitting effect at a small lag distance (Zhang,2005).

Semivariance analysis results show that the spherical and exponential model can fit the experimental semivariogram of SRE. For strip, narrow and wide basins, 93%, 91% and 95% of the experimental semivariogram of SRE can be better fitted using a spherical model, respectively. Others can achieve better fitting effect using exponential model. for these basins, Figure 2 presents the fitting curve using a spherical instead of an exponential model. Results show that at a small lag distance the replace error is small, the error mainly occurs with a large lag distance. It is feasible to use a spherical to replace an exponential model. So, the spherical model can be used to similarly describe the spatial variability of SRE for different type basins.

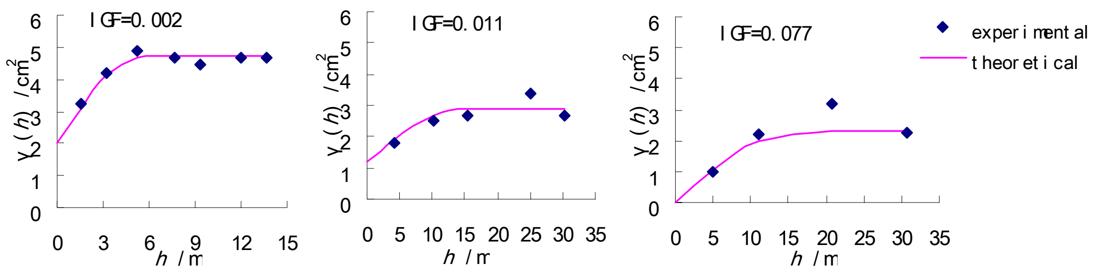


Figure 1. The Experimental and Theoretical Semivariogram of SRE for Different IGF

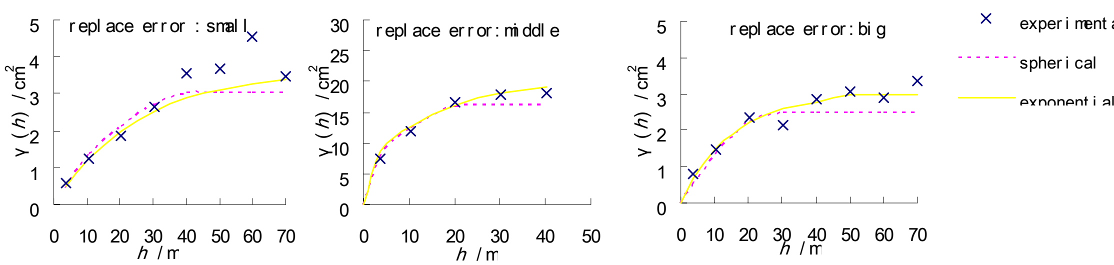


Figure 2. Typical Fitting Effect using Spherical instead of Exponential model

Table 3 summarizes the descriptive statistics for the semivariogram of SRE fitted by spherical model. For different basin types the average of $C_0/(C_0+C)$ is 0.21, 0.34 and 0.32, respectively, indicating medium and strong spatial correlation.

Table 3. Statistics of Semivariogram Parameters of SRE for Every Basin Type

Basin type	statistics	Semivariogram parameters				*IGF*
		Nugget (C_0 /cm^2)	*Sill*(C_0+C /cm^2)	$C_0/(C_0+C)$	*Range*(a /m)	
Strip basin	Maximum	2.20	22.00	0.67	60.00	0.097
	Minimum	0.00	0.80	0.00	5.00	0.002
	Mean	0.58	4.66	0.21	16.69	0.026
	variance	0.52	0.47	0.27	0.47	0.60
Narrow basin	Maximum	8.00	29.00	0.67	58.00	0.071
	Minimum	0.00	1.45	0.00	6.00	0.003
	Mean	2.95	10.56	0.34	19.91	0.009
	variance	0.63	0.62	0.64	0.54	0.49
Wide basin	Maximum	5.00	15.40	0.63	65.00	0.078
	Minimum	0.00	2.15	0.00	4.00	0.003
	Mean	1.92	6.89	0.32	25.83	0.012
	variance	0.75	0.53	0.56	0.67	0.53

Effect of Basin Geometry on the Spatial Variability Parameters of SRE

Table 4 presents the correlation between basin geometry parameters and the spatial variability parameters of SRE. Correlation coefficient (*r*) was used to quantify the correlation degree. For strip and narrow basin, the basin length (*L*) has medium or low correlation with sill (C_0+C). For all types high correlation is found between *L* and range (*a*), which shows that the effect of basin length on the range is strong. For strip basin the basin width (*W*) indicates low or no correlation with all spatial variability parameters, however, for narrow and wide basin, medium or high correlation exist between *W* and *a*, with *W* increase the effect of *W* on *a* becomes strong. For strip and narrow basin, the basin area(*A*) has middle or low correlation with C_0+C, for all types high correlation is found between *A* and *a*, basin area will obviously affect the range. High correlation is found between S_d and C_0+C for all types, S_d will obviously affect the sill. On the other hand, the influence of S_d on *a* is small, only for narrow basin the medium correlation is found. For all types the observation space (*d*) has bigger effect on the nugget(C_0), medium correlation is found, at the same time, medium or high correlation is found between *d* and *a*, which indicates the observation space will obviously affect the range. Above results show that basin length, width and area, and observation space are principal variable affecting range, S_d of SRE will obviously affect the sill, and the observation space still has stronger effect on nugget.

Table 4. Correlation Coefficient between Field Geometry Parameters and Spatial Variability Parameters of SRE

		C_0	C_0+C	$C_0/(C_0+C)$	a
Strip basin	length *L*	-0.29	0.40**	-0.30	0.98**
	width *W*	-0.28	0.21	-0.36*	0.05
	area *A*	-0.34*	0.42**	-0.38*	0.90**
	S_d	-0.16	0.98**	-0.35*	0.39*
	space *d*	-0.59*	0.31*	-0.39*	0.78**
Narrow basin	length *L*	0.26	0.56**	-0.01	0.84**
	width *W*	0.19	0.54**	-0.18	0.50**
	area *A*	0.11	0.63**	-0.19	0.72**
	S_d	0.13	0.94**	-0.33	0.65**
	space *d*	-0.69**	0.34*	-0.54**	0.67**
Wide basin	length *L*	0.33*	0.21	0.05	0.89**
	width *W*	0.25	0.22	0.01	0.91*
	area *A*	0.24	0.16	0.01	0.93**
	S_d	0.17	0.93**	-0.43**	0.35*
	space *d*	-0.70**	0.21	-0.31	0.87**

note：* significance level 0.05；** significance level 0.01

Calculation of Spatial Variability Parameters of SRE

For all basin types the sill has high correlation with S_d of SRE; highest correlation is found between L and a for strip and narrow basin, range has highest correlation with A for wide basin,. So, the sill can be calculated by the regression relation between sill and S_d (Table 5), while the range can be calculated by the regression relation between a and L for strip and narrow basin or between a and A for wide basin (Table 4). Medium correlation is found between nugget and d, when d is in the range of 1.5-10m. Eqs. 4 can be used to calculate C_0 ,

$$C_0 = \left[\frac{C_0}{C_0 + C}\right] \times (C_0 + C) = \left[\frac{C_0}{C_0 + C}\right] S_d^2 \qquad (4)$$

The value of $[C_0/(C_0+C)]$ in Eqs.4 was presented in Table 3. For any given field, based on the S_d of SRE the spatial variability parameters fitted through a spherical semivariogram can be estimated by the calculation equation in Table 5.

Table 5. Calculation Equation of Spatial Variability Parameters of SRE

basin type	C_0 /cm^2	$C_0 + C$ /cm^2	a /m
Strip basin	$0.21S_d^2$	S_d^2	$0.18L+1.53$
Narrow basin	$0.34S_d^2$	S_d^2	$0.21L-4.11$
Wide basin	$0.32S_d^2$	S_d^2	$16.69A+5.26$

MICROTOPOGRAPHY STOCHASTIC GENERATING MODEL

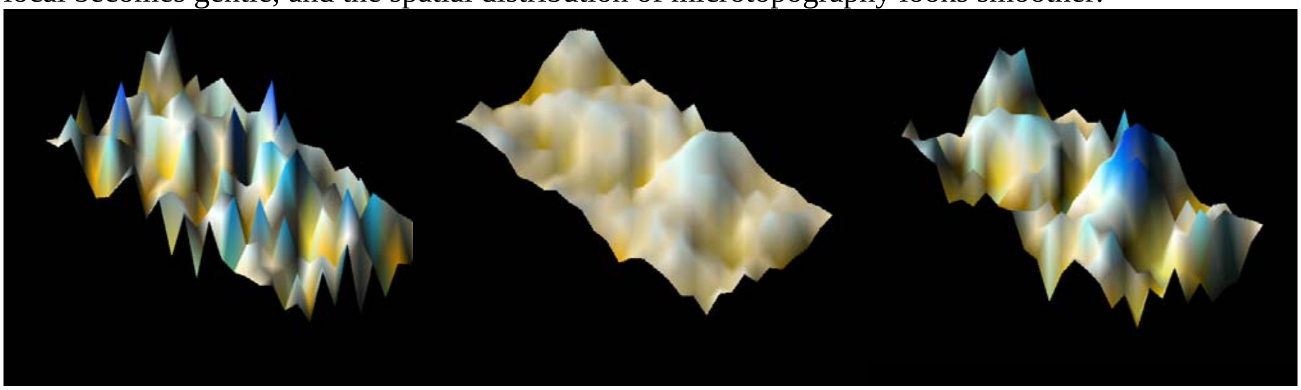
Microtopography Stochastic Generating Method

Stochstic Generating SRE Using the Monte-Carlo(M-C) Based on the statistical characteristics of SRE(Mean μ and S_d), a group of random number $R=(r_1, r_2, \ldots, r_i, \ldots, r_n)$ could be generated in the range of [0, 1] using the Monte-Carlo method, then according to the probability distribution of SRE the value of SRE $H=(h_1^0, h_2^0, \ldots, h_i^0, \ldots, h_n^0)$ corresponding to each random number could be calculated by inverse method. Where, h_i^0 is the value of SRE at the point i; n is the number of calculation node for the given field.

Modifying Value Range for the Stochastic Generating SRE The theoretical value range of the stochastic generating SRE is [-∞ , +∞], however, because of the requirement of farm cultivation, the value range of SRE is limited, which is related with the S_d of SRE. Considering the actual and theoretical requirement, the value range of SRE could be limited to the range $[\mu\text{-}3S_d , \mu + 3S_d]$. When the value of SRE was out of the range, the value was regarded as useless, and the value at this point needed to be regenerated using the M-C method.

Modifying Spatial Correlation Structure for the Stochastic Generating SRE The stochastic generating SRE is random not only the value but also the spatial distribution. The undulation of

SRE steeply changes in the small range (see Figure 3a). In order to make the generating microtopography is similar to the actual farm condition; kriging interpolation method was adopted to modify the spatial correlation of SRE. According to the spatial correlation structure of SRE, the value of SRE at point $i\,(i = 1, 2, \ldots, n)$ is estimated by the value of SRE of other points which are around the *i* in the range of *a*, and the original value at point *i* will be replaced by the estimated value. Figure 3b gives out the spatial distribution of microtopography after modifying the spatial correlation. Comparing with the Figure 3a, the trend of undulation change of SRE at local becomes gentle, and the spatial distribution of microtopography looks smoother.



a. Stochastic Generating b. Modifying Spatial Correlation c. Modifying Statistic Characteristics

Modifying Statistical Characteristics for the Stochastic Generating SRE Figure 3b shows that the spatial distribution of microtopography takes great change after modifying the value range and spatial correlation, and the given statistical characteristics of SRE at beginning are changed. So, in order to make the statistical characteristics equal to the given value, the statistical characteristics need to be further modified after modifying the spatial correlation of SRE. First the mean of SRE was modified by Eq. 5, and then the standard deviation of SRE was modified by Eq. 6.

$$h_i^2 = \frac{\mu}{\mu_1} h_i^1 \tag{5}$$

$$h_i^3 = (h_i^2 - \mu)\frac{S_d}{S_{d2}} + \mu \tag{6}$$

Where, h_i^1、 h_i^2 and h_i^3 respectively is the value of SRE at point *i* after modifying the spatial correlation, mean and standard deviation; μ_1 is the mean of SRE after modifying the spatial correlation; S_{d2} is the standard deviation of SRE after modifying the mean.

Figure 3c presents the spatial distribution of microtopography after modifying the value range, spatial correlation, mean and standard deviation, which not only keeps the whole relief of microtopography but also make the micro-relief is more similar to the actual farm status.

Determining Reasonable Sample Content

The SRE can be generated by the microtopography stochastic generating method. However, the spatial distribution of SRE for the same characteristics (μ and S_d) may not be unique. In practice, we must determine how many samples need to be generated for the given μ and S_d to reflect the real microtopography situation. This leads to the determination of reasonable sample content for generating of the SRE.

Assuming all possible microtopography distributions for the same characteristics consist of the population, any one kind of distribution is regarded as individual. Basin microtopography condition is up to the value of SRE at different points and their spatial distribution. It is difficult to quantificationally describe the microtopography distribution using one indicator. However, for a given microtopography distribution, the irrigation performance is unique when other irrigation factors are the same. So, the sample content of generating microtopography can be determined by analyzing the variation tendency of the irrigation performance indicators through numerical simulation experiments. *N* microtopography distributions are generated for the same statistic characteristics, and *N* irrigation performances corresponding to the different distribution are obtained by irrigation simulation. The number of individual *m* (m<*N*) to reflect the effect of the population of microtopography distribution on the irrigation performance can be obtained by analyzing the change of irrigation performance with the number of individual.

Numerical Simulation Experiment Design Basin size and S_d of SRE were considered in numerical simulation experiments to decide sample content. According to Table.1, basin size is set as 100m×5m, 150m×20m and 100m×50m for strip, narrow and wide basin respectively. S_d is set six levels as 1cm, 2cm, 3cm, 4cm, 5cm, 6cm. Therefore, eighteen basin conditions could be supplied for numerical simulations by combining every level of basin size and S_d of SRE. For each basin condition, 200 microtopography distributions with the same S_d were generated by microtopography stochastic generating model, and the corresponding 200 groups of irrigation performance (*CU*, E_a, Z'_{avg}) could be obtained by simulating the irrigation process. Parameters needed for running B2D were determined according to the typical situation of surface irrigation system in North China.

Numerical Simulation Results Figure 4 and Figure 5 respectively present the relationship between the mean and standard deviation of Z'_{avg}, E_a and *CU* and the sample content (simulation number) for narrow basin. Results show that with the increase of sample content the mean and standard deviation of Z'_{avg}, E_a and *CU* become stable. The results are similar to the narrow basin and for wide and strip basin.

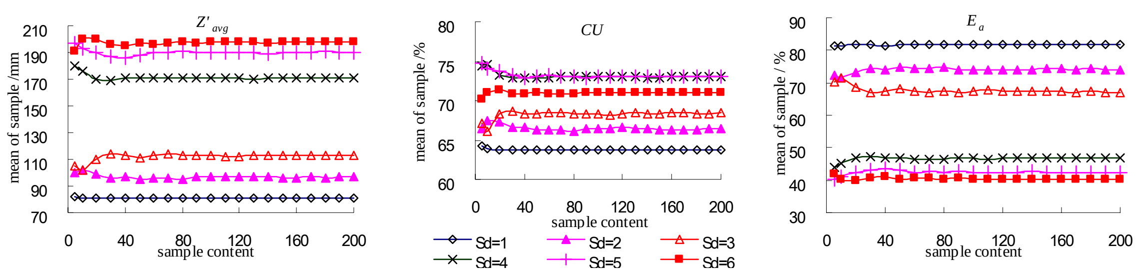


Figure 4. The relationship between the mean of Z'_{avg}, E_a and *CU* and sample content

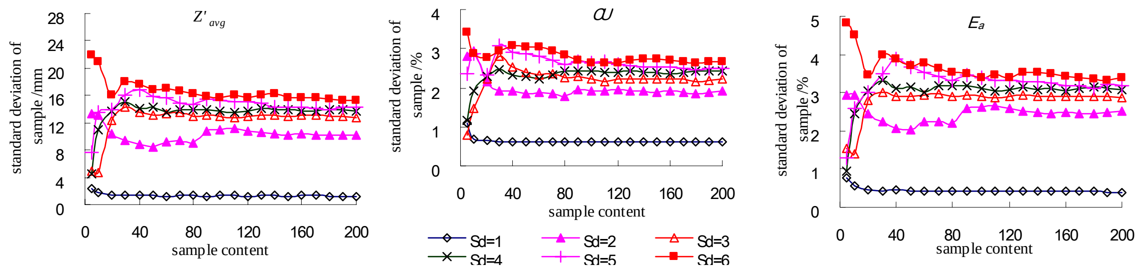


Figure 5. The relationship between the standard deviation of Z'_{avg} , E_a and CU and sample content

<u>Determining Reasonable Sample Content</u> For the same undulation degree of microtopography, the spatial distribution of undulation location is not unique and independent each other. Therefore, the corresponding Z'_{avg}, E_a and CU can be regarded as independent random variables, and K-S test results show that their probability distribution meets normal distribution. According to the law of large number, at the condition of independent sampling, the mean of population can be replaced by the mean of the stable sample (Deng, 2002). Numerical simulation experiment results show that the mean and standard deviation of Z'_{avg}, E_a and CU become stable with the increase of sample content. So the mean and standard deviation of population of Z'_{avg}, E_a and CU can be replaced by the stable value. The reasonable sample content could be determined by the interval estimation formula of single population mean.

For the population of independent random variable X~N(μ, σ^2), if X_1, X_2, …, X_m are samples from X, when σ^2 is known and the confidence level is α, the interval estimation of population mean μ is following (Deng, 2002)

$$\left[\overline{X}-\frac{\sigma}{\sqrt{m}}Z_{\alpha/2},\qquad \overline{X}+\frac{\sigma}{\sqrt{m}}Z_{\alpha/2}\right] \qquad (7)$$

For a given estimation precision l_0 the interval distance $2\sigma\cdot Z_{\alpha/2}/\sqrt{m}$ is required to be less than $2l_0$,i.e.

$$2\sigma\frac{Z_{\alpha/2}}{\sqrt{m}}\le 2l_0 \qquad (8)$$

Thus, sample content must meet following equation

$$m\ge(\sigma\frac{Z_{\alpha/2}}{l_0})^2 \qquad (9)$$

Where σ is the standard deviation of population, the value is replaced by the stable value of samples.The precision l_0 for Z'_{avg}, E_a and CU are set as 5mm, 1% and 1%.The confidence level α is set as 0.05. Then the minimum sample content for each basin condition could be calculated by Eqs.9.

Table.6 presents the minimum sample content for different estimation precision and basin condition. Results show that the difference of the minimum sample content calculated by Z'_{avg},

E_a and *CU* are big. In order to make the sample content simultaneously meet the estimation precision of Z'_{avg}, E_a and *CU*, the maximum of the minimum sample content of Z'_{avg}, E_a and *CU* is chosen as the reasonable sample content for the random generating of the microtopography. For example,the reasonable sample content of the strip basin is 33 when the value S_d of is 2cm.

Table 6.The Minimum Sample Content for Different Estimation Precision and Basin Conditions

Basin type	Performance indicator	precision l_0	minimum sample content S_d=1	S_d=2	S_d=3	S_d=4	S_d=5	S_d=6
Strip basin	Z'_{avg}	5mm	1	7	20	28	39	54
	E_a	1%	1	16	48	53	56	65
	CU	1%	1	33	37	48	53	56
Narrow basin	Z'_{avg}	5mm	1	17	26	30	32	38
	E_a	1%	1	24	33	38	40	45
	CU	1%	1	14	19	23	24	28
Wide basin	Z'_{avg}	5mm	1	11	17	14	37	45
	E_a	1%	1	26	31	35	45	49
	CU	1%	1	22	24	31	32	37

Validating Microtopography Stochastic Generating Method

According to the field observation data, the microtopography stochastic generating method was validated by comparing the Z'_{avg}, E_a and *CU* corresponding to the observed microtopography condition and the generated microtopography condition. First, based on the observation data such as basin size, microtopography condition, infiltration parameters, inflow condition and so on, the Z'_{avg}, E_a and *CU* corresponding to observed microtopography could be obtained by the simulation of the irrigation process of the each experiment field. Similarly, the Z'_{avg}, E_a and *CU* corresponding to generated microtopography condition could also be obtained by the simulation with the microtopogrphy conditions generated by the model.

Validating Condition of Microtopography Stochastic Generating Method Five typical basins with different basin size and microtopography condition were chosen to validate the microtopography stochastic generating method. Table.7 presents the basic condition of all typical fields. When estimation precision of Z'_{avg}, E_a and *CU* is 5mm, 1%and1%, the reasonable sample content m_i (i=1, 2, 3, 4, 5) of microtopography stochastic generating for each typical field can be decided according to Table.6, which are 1, 26, 48, 33, 35. Combining the microtopography stochastic model with irrigation model B2D, m_i groups of Z'_{avg}, E_a and CU corresponding to m_i groups of microtopography condition for each typical field could be obtained.

Table 7.Basic Condition of Typical Experiment Fields

Field number	1	2	3	4	5
Basin size (long×wide) / m	100×20	40×20	90×10	100×20	30×15
Mean of SRE / cm	2.15	3.25	8.47	7.10	8.68
S_d of SRE / cm	1.0	1.5	2.7	3.0	4.0

Validating Results Figure 6 presents the observation and the maximum, minimum and mean of simulation of Z'_{avg}, E_a and CU for each typical field, respectively. All observations are located inside of the value range of simulation. Theoretically, the actual microtopography condition of typical field is only one representation of all possible microtopography conditions corresponding to the S_d of this typical field. The results in Figure 6 indicate that if the basin size and S_d are given, m_i microtopography conditions generated by microtopography stochastic model according to the sample content in Table.6 can reflect the actual microtopography.

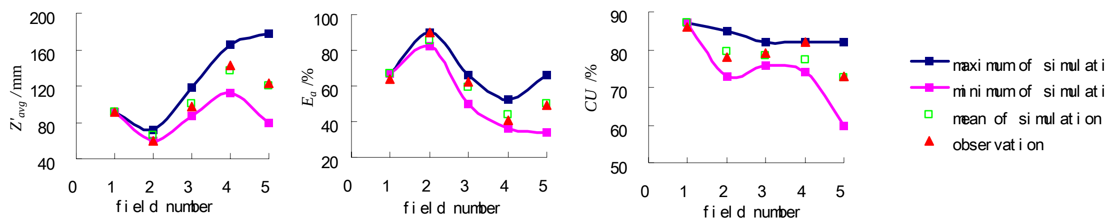


Figure 6. The Observation and Simulation of irrigation Performance of Typical Fields

Table 8 presents the relative error between observation and the mean of simulation of Z'_{avg}, E_a and CU. Results show that the relative errors are all less than 10%, and except for the Z'_{avg} of number 2 and the E_a and CU of number 4, the relative errors of Z'_{avg}, E_a and CU for other basins are all less than 5%. So, for any given basin condition, it is feasible to evaluate the irrigation performance by stochastic generating microtopography data.

Table 8.The Relative Error between Observation and Average Simulation of Irrigation Performance

	Relative error / %				
	1	2	3	4	5
Z'_{avg}	0.8	8.5	2.2	4.7	2.9
E_a	4.5	4.8	4.5	7.6	2.0
CU	1.3	1.7	1.0	5.7	0.8

EFFECT OF SPATIAL VARIABILITY OF MICROTOPOGRAPHY ON THE BASIN IRRIGATION PERFORMANCE

Numerical Experiment

An example of wide basin (100m×40m) was used to analyze the effect of spatial variability of microtopography on basin irrigation performance. Six levels were set for undulation degree of microtopography (S_d=1, 2, 3, 4, 5, 6cm). For each S_d, m_i (i=1, 2, …, 6)groups of microtopography condition were generated. According to Table.6, m_i (i=1, 2,…,6) was 1, 26, 31, 35, 45 and 49 respectively. When the irrigation process corresponding to each microtopography condition was simulated, the infiltration parameters took example for loam soil, the inflow was $4L.m^{-1}.s^{-1}$, and the irrigation time was controlled as the water justly covering the whole basin. The calculation grid was 4m×4m.

Effect of Spatial Variability of Microtopography on the Basin Irrigation Process

Advance time, recession time and opportunity time are the main hydraulic characteristic parameters to describe the basin irrigation process. Statistic parameters (range, mean, coefficient of variation C_v) of these hydraulic parameters were analyzed to understand the effect of spatial variability of microtopography on the basin irrigation process. The range, mean and C_v of advance time respectively means the difference of advance time between the first point and the last point where the water cover, and the mean and variability of advance time at all calculation points. The range, mean and C_v of recession time respectively mean the difference of recession time between the first point and the last point where the water disappear, and the mean and variability of recession time at all calculation points. The range, mean and C_v of opportunity time respectively mean the difference of opportunity time between the maximum and the minimum, and the mean and variability of opportunity time at all calculation points.

Figure 7 presents the relationship between the coefficient of variation (C_v) of m_i groups of statistic parameters (range, mean, C_v) corresponding to m_i groups of microtopography condition and the value of S_d, which reflects the effect of undulation degree and the distribution difference of undulation location on the irrigation process.With the increase of S_d, the C_v of the statistic parameters (range, mean, C_v) increase. The change trend of C_v of statistic parameters of advance time is relative gentle, and the maximum is less than 0.2. It shows when S_d is in the rang of 1-6cm the effect of distribution difference of undulation location on the advance phase is small. However, the change trend of C_v of statistic parameters of recession and opportunity time is relative steep, the effect of distribution difference on the recession phase is more obvious.

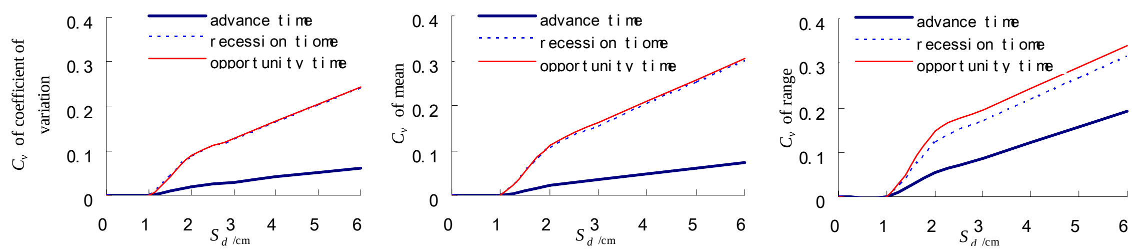


Figure 7. Relationship between C_v of Statistic Parameters of Advance, Recession and Opportunity and S_d time and S_d

Effect of Spatial Variability of Microtopography on the Basin Irrigation Performance

Table 9 presents the value range and mean of m_i groups of irrigation performance corresponding to m_i (m_i=1, 26, 31, 35, 45, 49) microtopography conditions for different undulation degree (S_d ＝1, 2, 3, 4, 5, 6cm). With the increase of S_d, Z'_{avg} obviously increases, and E_a and *CU* obviously decreases. When S_d increases from 0cm to 6cm, Z'_{avg} increases from 82mm to 170mm, E_a decreases from 97% to 49%, and *CU* decreases from 95% to 68%. The value range gradually increases, and when S_d>2cm the change trend is more obvious. Results showes with the increase of S_d the irrigation performance decreases, the effect of distribution difference of undulation location on irrigation performance increases.

Table 9. The Range and Mean of m_i Groups of Irrigation Performance

S_d /cm		0	1	2	3	4	5	6
Z'_{avg} /mm	Range	82-82	86-86	90-135	102-164	110-175	91-241	112-263
	mean	82	86	116	132	151	165	170
CU /%	Range	95-95	91-91	83-90	76-86	72-83	55-85	54-83
	mean	95	91	85	80	77	72	68
E_a /%	Range	97-97	91-91	60-86	49-76	39-68	33-71	32-72
	mean	97	91	69	60	53	51	49

Figure 8 presents the relationship between the coefficient of variation (C_v) of m_i groups of irrigation performance (Z'_{avg}, E_a and *CU*) corresponding to m_i groups of microtopography condition and the value of $S_{d,}$, which compositively reflects the effect of spatial variability (difference of undulation degree and undulation location distribution) of microtopography on the irrigation performance. Figure 8 shows that with the increase of S_d the C_v of Z'_{avg} and E_a gradually increase, and when S_d is in the range of 1-2cm or more than 4cm the change trend is steep. However, the increase trend of C_v of *CU* is relative slow, the maximum is no more than 0.1. Results shows that when S_d<2cm, the effect of distribution difference of undulation location on the irrigation performance is very small, and the C_v is less than 0.1. When 2cm≤S_d≤4cm, the effect is relative small, the change trend is very gentle. When S_d>4cm, the effect increases obviously.

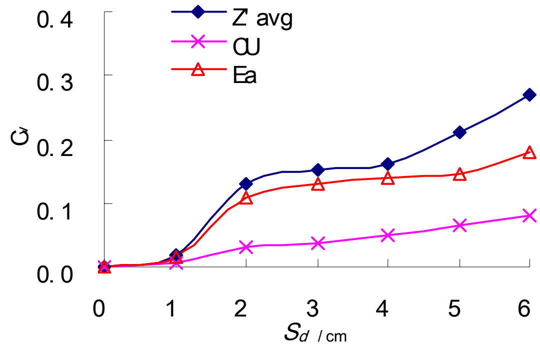


Figure 8. The Relationship between the C_v of Irrigation Performance and S_d

CONCLUSION

The size of 116 typical fields analyzed in this paper basically present all the field geometry characteristics of different irrigation districts in North China. The results based on the observation data showed that the medium or strong spatial correlation was found for microtopography, and the spatial variability structure could be described using spherical model. For the arbitrary given field, the parameters of semi-variogram fitted through a spherical model could be estimated according to S_d and the empirical equation in Table.5.

The effect of microtopography spatial variability on the basin irrigation performance was evaluated by microtopography stochastic generating model and irrigation model. The results showed that the microtopography undulation degree and the distribution difference of undulation location had obvious effect on the basin irrigation performance. The Z'_{avg} increased and E_a and *CU* decreased with the increase of S_d. When S_d increased from 0cm to 6cm, Z'_{avg} increased from 82mm to 170mm, E_a decreased from 97% to 49%, and *CU* decreased from 95% to 68%. The effect of the distribution difference of undulation location on the irrigation performance was dependent upon the microtopography undulation degree. When the S_d was less than 2 cm the effect was small, which could be neglected. While S_d was more than 2cm, the influence degree became obvious, which should be considered.

REFERENCES

Burrough, P.A. Sampling designs for quantifying map unit composition. In M.J. Mausbach and L.P. Wilding (eds.), Spatial Variabilities in Soils and Landforms. Soil Sci. Soc. Am., Spec. Pub. 28, Madison, WI, 1991, 89-125.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., et al. Irrigation performance measures: efficiency and uniformity. Journal of irrigation and drainage engineering, ASCE, 1997, 123(6): 423-442.

Clemmens, A.J.and Z.El-Haddad, et al, Assessing the potential for modern surface irrigation in Egypt, Transactions of the ASAE, 1999, 42(4):995-1008.

Deng, H.N.. Method and Application of probability statistic.Beijing: China Agriculture Press, 2002.

Li, N., D.Xu, and F.X.Li. Study on influences of field leveling precision on border irrigation quality and crop field.[J]. Journal of Hydraulic Engineering, 2000, 12: 82-87.

Li,Y.N., Xu.D.,and Li,F.X..Modeling on the influence of land leveling Precision on basin irrigation performance.Transactions of the CSAE.2001, 17(4):43-48.

Pereira.L S, Feddes R A and Gilley J R, *et al*. Sustainability of irrigated agriculture Netherlands: Kluwer Academic publishers, 1996.

Playan E and Faci J M. Characterizing microtopographical effects on level-basin irrigation performance. Agricultural Water Management, 1996a, 29:129-145.

Playan, E. and Faci, J.M.. Modelling micro topography in basin irrigation. Journal of Irrigation and Drainage Engineering, ASCE, 1996b, 122(6): 339-347.

Playan, E.. Two-dimensional simulation of basin irrigation: I: THEORY. Journal of Irrigation and Drainage Engineering, ASCE, 1994a, 120(5): 837-856.

Playan, E.. Two-dimensional simulation of basin irrigation: II: APPLICATIONS. Journal of Irrigation and Drainage Engineering, ASCE, 1994b, 120(5): 857-869.

Pannatier, Y.. VARIOWIN: Software for Spatial Data Analysis in 2D, Springer-Verlag, New York. 1996.

Xu, D., Y. N. Li , F.X.Li .et al. Study and application of the water saving irrigation technology at farm.Beijing: China Agriculture Press, 2002.

Xu, D.,Li,Y.N.,et al. Analysis of feasible grid space in agricultural land levelling survey. Transactions of the CSAE.2005, 21(2):51-55.

Yu, J.Y.,He,X.H.,Statistical analysis of data and apply of SPSS. Beijing：The post of people Press,2003.

Zapata, N. and Playan, E.. Elevation and infiltration in a level basin. I. Characterizing variability. Irrigation Science, 2000, 19: 155-164.

Zhang, R.D. Theory and apply of spatial variability. Beijing：Science press，2005.

DRIP IRRIGATION AS A SUSTAINABLE PRACTICE UNDER SALINE SHALLOW GROUND WATER CONDITIONS

Blaine R. Hanson[1]
Don M. May[2]
Jan Hopmans[3]
Jirka Simunek[4]

ABSTRACT

Subsurface drainage systems cannot be used for addressing the saline, shallow ground water conditions of the San Joaquin Valley, California because no drainage water disposal facilities exist in the valley. Thus, the salinity/drainage problem of the valley must be addressed through improved irrigation practices such as converting to drip irrigation. Experiments in four commercial fields evaluated the effect of subsurface drip irrigation on processing tomato yield and quality, soil salinity, soil water content, and water table depth. The HYDRUS-2D computer simulation model evaluated leaching with subsurface drip irrigation under saline, shallow ground water conditions. Drip irrigation of processing tomatoes was highly profitable under these conditions compared to sprinkle irrigation. No trend in tomato yield was found with soil salinity levels. A water balance showed little or no field-wide leaching in the commercial fields, yet soil salinity data and computer modeling clearly showed localized leaching around the drip lines.

INTRODUCTION AND BACKGROUND

About 400,000 ha of salt affected irrigated land exist along the west side of the San Joaquin Valley, California. Upward flow of the saline, shallow groundwater is the main source of the salts. Subsurface drainage systems, traditionally used for coping with shallow ground water problems, cannot be used because no economically, technically, and environmentally feasible drain water disposal method exists for the valley. Thus, options such as better management of irrigation water to reduce drainage below the root zone, increasing crop water use of the shallow groundwater without any yield reductions, and drainage water reuse for irrigation must be implemented to deal with the shallow ground water conditions (Hanson and Ayars, 2002). Shoups et al., (2005) concluded that for irrigated agriculture to remain sustainable, a soil salt balance must be maintained that allows for productive cropping systems and continued irrigation without changing management practices is not sustainable.

Converting from furrow or sprinkler irrigation to drip irrigation is one option for growers in the salt affected areas. Drip irrigation can apply water both precisely and uniformly compared with

[1] Irrigation and Drainage Specialist, Dept. of Land, Air and Water Resources, University of California, Davis, CA 95616; brhanson@ucdavis.edu
[2] Farm Advisor (Emeritus), University of California Cooperative Extension, Fresno County, Fresno, CA; dmay@ucdavis.edu
[3] Professor, Dept. of Land, Air and Water Resources, University of California, Davis, CA 95616;jwhopmans@ucdavis.edu
[4] Professor, Dept. Environmental Sciences, University of California, Riverside CA 92521; Jiri.Simunek@ucr.edu

furrow and sprinkler irrigation thus potentially increasing yield, reducing root zone soil salinity, and reducing subsurface drainage. This potential is not only governed by the technology, but also design, installation, operation, and maintenance of drip irrigation systems. The main disadvantage of drip irrigation is its cost, which can be as much as \$2,470 ha^{-1}.

For drip irrigation to be sustainable, it must be profitable. Yet, several large-scale comparisons of furrow and drip irrigation of cotton revealed mixed economic benefits of drip irrigation. At one location, furrow irrigation was clearly more profitable than drip irrigation (Fulton et al., 1991), while at a second location, drip irrigation was slightly more profitable (Styles et al., 1997). Thus, growers converting to drip irrigation of cotton face uncertainty about the economic risks involved.

Subsurface drip irrigation of high-cash value processing tomatoes has a potential for high profits compared to cotton. However, tomatoes are more salt sensitive than cotton, creating a potential for reduced tomato yields in salt affected soil. The effect of subsurface drip irrigation of processing tomatoes was evaluated under saline, shallow ground water conditions to determine its effect on crop yield and quality, soil salinity, leaching fraction, water table depth, and profitability.

METHODS AND MATERIALS

Field experiments were conducted in four commercial fields to determine the effect of subsurface drip irrigation. In addition, the computer simulation model HYDRUS-2D was used to evaluate leaching with subsurface drip irrigation under saline, shallow ground water conditions.

Field Experiments

Experiments in three commercial fields compared subsurface drip irrigation of processing tomatoes with sprinkle irrigation under saline, shallow ground water conditions. The drip irrigation systems ranged from 16 ha to 32 ha in size with drip lines buried 0.2 to 0.30 m deep and drip line lengths of 400 m. Drip irrigations occurred every two to three days. Water table depths ranged from 0.5 m to 2 m, depending of the field location. The electrical conductivity (EC) of the irrigation water ranged from 0.30 to 0.35 dS m^{-1} (irrigation district water) to 1.06 to 1.2 dS m^{-1} (well water). The EC of the shallow ground water ranged from 4.7 dS m^{-1} to 16.4 dS m^{-1}, depending on the particular field and time of year. Soil type was clay loam at the three sites. In addition, a small-plot randomized block replicated experiment was superimposed on each drip system with irrigation treatments consisting of different amounts of irrigation water to determine the minimum amount of water needed for maximum yield under saline, shallow ground water conditions.

At a fourth commercial field where saline, shallow ground water was about 0.45 m to 0.6 m deep, a small-scale randomized block replicated experiment evaluated the effect of applied water amounts on processing tomatoes and cotton yield. Drip irrigations occurred daily. The electrical conductivity of the irrigation water was 0.52 dS m^{-1}. The electrical conductivity of the shallow ground water ranged from 8 to 11 dS m^{-1}.

Computer Simulations

The computer simulation model HYDRUS-2D (Šimůnek et al., 1999) was used to evaluate leaching with subsurface drip irrigation under saline, shallow ground water conditions by simulating soil water and soil water salinity distributions around drip lines. Output of the simulations were the distributions of soil water, soil water salinity, and pressure head around the drip line; salt mass and volume of soil water in the profile; and amount of drainage below the root zone. This model has been previously used in studies of water and chemical movement under drip irrigation (Gardenas et al., 2005; Hanson et al., 2006).

System design characteristics used for the simulations were typical of the subsurface drip systems used for processing tomatoes. Drip line depth was 20 cm; emitter spacing was 30 cm; and low flow drip tape was used . A line-source model with a rectangular geometry was used because of the multiple closely-spaced outlets along the drip line. The model domain was the top 100 cm of a soil profile extending 75 cm from the drip line, which represents the area explored by roots based on field experience and measurements. The boundary condition along the sides of the domain was no water flux; the boundary condition at the bottom of the domain was constant pressure representing the position of the ground water table; an atmospheric boundary condition was used at the top of the domain. The constant pressure boundary at the bottom of the domain allowed water draining below the drip line to flow out of the domain without raising the water table, which provided an estimate of the potential leaching fraction below the root zone.

Simulations were conducted for water table depths of 0.5 and 1.0 m, irrigation water salinities of 0.3, 1.0, and 2.0 dS m^{-1}, and applied water amounts of 80, 100, and 115% of the potential evapotranspiration. For the EC = 0.3 dS m^{-1}, an additional water application of 60% was also conducted. Two irrigations per week occurred for the 1.0 m water table depth; daily irrigations occurred for the 0.5 m depth. EC's of shallow ground water were 10.0 dS m^{-1} and 8.0 dS m^{-1} for the 0.5 and 1.0 m water table depths, respectively, based on the field measurements. The initial soil water salinity levels at the start of the simulation period were based on field measurements. Simulations were conducted for a 42 day period.

RESULTS AND DISCUSSION

Field Experiments

Yields of the three large-scale subsurface drip systems exceeded those of sprinkle irrigation by 12.1 Mg ha^{-1} to 22.6 Mg ha^{-1} (Hanson & May, 2004). Average yields were 93.7 Mg ha^{-1} and 74.8 Mg ha^{-1} for subsurface drip irrigation and sprinkle irrigation, respectively, statistically significant for $\alpha = 0.05$ (t-test). Tomato yield was unaffected by the range of soil salinity levels measured in these fields, which ranged from levels smaller than the threshold level of 2.5 dS m^{-1} (Mass and Grattan, 1999) for tomatoes to levels exceeding the threshold soil salinity. (The threshold soil salinity, expressed as the electrical conductivity of the saturated extract, is the maximum root zone soil salinity at which no yield reductions occur.) The average difference in soluble solids between the two irrigation methods was not statistically significant. In the small plot experiments, yields decreased as applied water decreased and soluble solids increased as applied water decreased. Based on the average yield increase and a crop price of \$55 Mg^{-1}, drip irrigation increased profits by \$1284 ha^{-1} more than those under sprinkle irrigation.

At the fourth site, tomato yields in the small-scale randomized replicated experiment ranged from 77.5 Mg ha^{-1} for 396 mm of applied water to 95.9 Mg ha^{-1} for 589 mm of water (about equal to the seasonal evapotranspiration) (Hanson et al., 2006). The regression between yield and applied water was highly significant at a level of significance of 0.05 (P = 0.0008). Cotton yield was unaffected by amount of applied water for amounts equal to or greater than about 40% of the potential crop evapotranspiration.

Soil salinity levels around drip lines depended on depth to the ground water, salinity of the shallow ground water, salinity of the irrigation water, and amount of applied water. For water table depths of 2 m, soil salinity levels (expressed as the EC of a saturated extract) smaller than the threshold salinity occurred and were relatively uniform around the drip line (fig. 1A). For water table depths of less than 1 m, salinity varied considerably with the smallest levels near the drip line and highest near the periphery of the wetted volume (fig. 1B). Higher values of soil salinity occurred near the drip line for the higher EC irrigation water (fig. 1C). Larger water applications increased the zone of low salt soil around drip lines (fig. 2).

The key to the profitability and sustainability of subsurface drip irrigation under saline, shallow ground water conditions is salinity control. Salinity control requires leaching or flushing of salts from the root zone by applying irrigation water in excess of the soil moisture depletion. The leaching fraction, used to quantify leaching adequacy, is the ratio of the amount of water draining below the root zone to the amount applied.

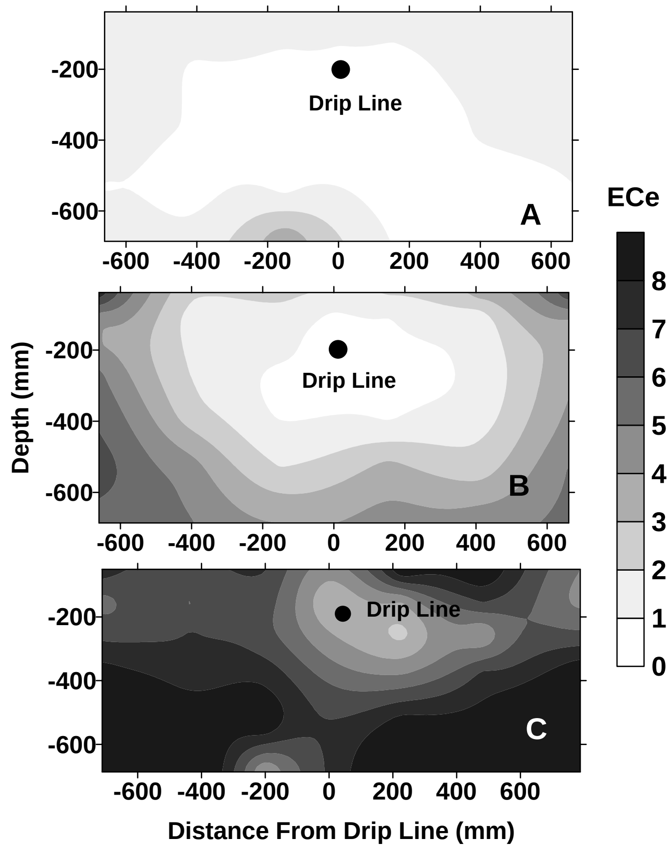


Figure 1. Patterns of soil salinity around drip lines for (A) an average water table depth = 2 m, EC of the irrigation water = 0.3 dS m^{-1}, and ground water EC = 8 to 11 dS m^{-1}; (B) water table depth between 0.61 and 1 m, EC of the irrigation water = 0.3 dS m^{-1}, and ground water EC = 5 to 7 dS m^{-1}; and (C) water table depth between 0.61 and 1 m, EC of the irrigation water = 1.1 dS m^{-1}, and ground water EC = 9 to 16 dS m^{-1}. The black dots are the drip line locations. Values are EC of saturated extracts (dS m^{-1}).

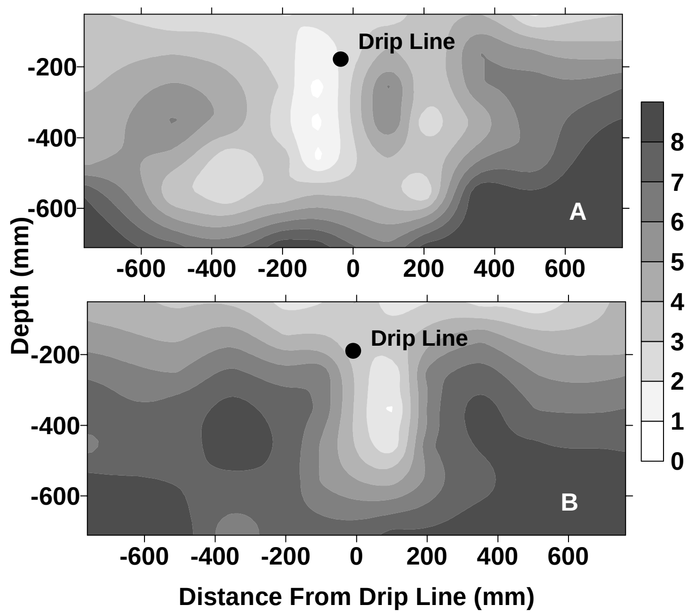


Figure 2. Effect of amount of applied irrigation water on the patterns of soil salinity around the drip line for (A) 589 mm of applied water (about equal to the seasonal evapotranspiration), and (B) 397 mm of applied water. EC of the irrigation water = 0.52 dS m^{-1} and the EC of the shallow ground water = 8 to 11 dS m^{-1}. The black dots are the drip line locations. Values are EC of saturated extracts (dS m^{-1}).

Leaching fractions can be determined several ways. One approach is to measure the average root zone soil salinity and the salinity of the irrigation water and then use appropriate charts or equations to determine the leaching fraction (Ayers and Westcott, 1985). However, because soil salinity, soil water content, and root density all vary around the drip line, some uncertainty exists in determining the average root zone salinity, and thus, leaching fraction, under drip irrigation.

A second approach commonly used is the water balance method which calculates the field-wide amount of leaching as the difference between seasonal amount of applied water (measured with a flow meter) and evapotranspiration. Field-wide leaching fractions were calculated for the commercial fields using the water balance approach. These calculations showed little or no field-wide leaching at most of the sites (table 1), suggesting the possibility of inadequate salinity control and raising questions about the sustainability of drip irrigation. The soil salinity data, however, clearly showed that because of the spatially varying wetting under drip irrigation, substantial leaching was occurring near the drip lines (referred to as localized leaching herein) and that the leaching was highly concentrated near the drip line. It is reasonable to expect that these salinity patterns reflect long-term patterns as long as adequate amounts of low salt irrigation water are applied and no ground water intrusion occurs into the root zone. The soil salinity data indicated that the water balance approach is not appropriate for drip irrigation.

Table 1. Seasonal applied water, evapotranspiration, and field-wide leaching fractions calculated from a water balance for the four commercial sites.

Year	Seasonal applied water (inches)	Seasonal evapotranspiration (inches)	Leaching fraction (%)
		BR	
1999	406	516	0
2000	427	544	0
2001	521	582	0
		DI	
1999	564	638	0
2000	737	640	13.1
2001	582	676	0
		DE	
2000	732	615	13.6
2001	561	587	0
		BR2	
2002	589	617	0

Computer Simulations

The simulated patterns of soil water salinity of the HYDRUS-2D model were similar to the soil salinity patterns found in the commercial fields, and showed that the soil was reclaimed rapidly under subsurface drip irrigation (fig. 3). The volume of reclaimed soil increased with time with most of the reclamation occurring below the drip line while salt accumulated above the drip line. The larger the amount of applied water, the larger the volume of reclaimed soil below the drip line (data not shown), behavior which is similar to that in Figure 2. However, the simulation data show that considerable leaching occurred around the drip line for water applications of 60 and 80 percent, normally considered to be deficit irrigation conditions with no field-wide leaching (data not shown).

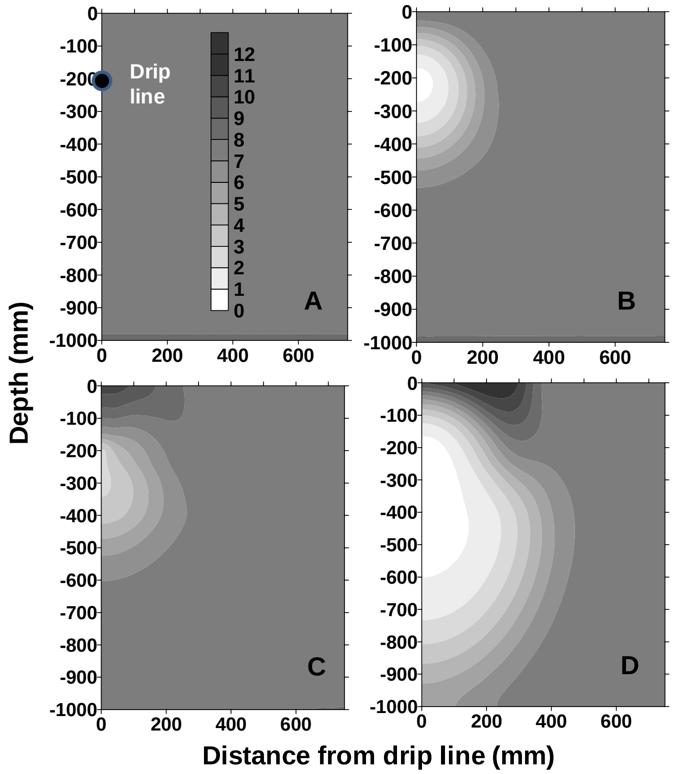


Figure 3. Simulated patterns of soil water salinity around drip lines for (A) prior to initiation of drip irrigation; (B) at the end of the first irrigation; (C) just before the second irrigation; and (D) at the end of the last irrigation. EC of the irrigation water = 0.3 dS m^{-1}; applied water = 100%; water table depth = 1.0 m.

Actual or localized leaching fractions ranged from 7.7% (60% water application) to 30.9% (115% water application), and was 24.5% for the 100% water application (table 2). As the salinity of the irrigation water increased, localized leaching fractions increased for a given amount of applied water because of reduced root water uptake. Thus, even for applications less than potential ET, considerable localized leaching occurred around the drip lines, reflecting the spatially-varying wetting around the drip line. This localized leaching is highly concentrated near the drip line, an area where root densities are likely to be the highest.

Table 2. Amount of applied water, root uptake, drainage (amount of water flowing out of the bottom of the domain), and localized leaching fraction (expressed as a percentage) for different amounts of applied water (expressed as a percentage of the potential crop evapotranspiration) and different irrigation water salinities (EC_i) for the simulated conditions. Water table depth was 1.0 m. Similar results occurred for the 0.5 m depth water table conditions.

Applied Water (%)	Applied water (cm^2)	Root uptake (cm^2)	Drainage (cm^2)	Leaching fraction (%)
		EC_i = 0.3 dS/m		
60	1410	1350	109	7.7
80	1890	1580	328	17.3
100	2360	1760	600	24.5
115	2710	1850	837	30.9
		EC_i = 1.0 dS/m		
80	1890	1440	431	22.8
100	2360	1610	719	30.4
115	2710	1700	962	35.4
		EC_i = 2.0 dS/m		
80	1890	1260	585	30.9
100	2360	1390	899	38.1
115	2710	1480	1150	42.4

CONCLUSIONS

Conclusions of both field research and computer simulation modeling are:

● Subsurface drip irrigation of processing tomatoes is highly profitable compared to sprinkle or furrow irrigation under saline, shallow ground water conditions.
● Tomato yield increased as applied water increased; cotton yield was unaffected by applied water amounts for water applications equal to or exceeding 40 percent of the potential evapotranspiration.
● Root uptake of the saline, shallow ground water by tomatoes should be minimized to prevent yield reductions; root uptake of the ground water by cotton should be encouraged.
● Considerable localized leaching occurs under subsurface drip irrigation due to the spatially-varying wetting around drip lines. The localized or actual leaching fraction was about 25% for a water application equal to 100% of the potential evapotranspiration.
● The localized leaching is highly concentrated near the drip line, resulting in relatively low soil salinity levels in the area where root density has been found to be the highest under subsurface drip irrigation of processing tomatoes.
● The water balance approach is inappropriate for estimating leaching fractions under drip irrigation.
● Little water table response to drip irrigation occurred except when overirrigation occurred.

● Reclamation around newly installed drip lines in saline soil was rapid. The reclamation was faster for relatively large water applications per irrigation applied less frequently than for smaller applications per irrigation applied more frequently.
● The low salt zone around the drip line increased as the amount of applied water increased.
● Soil salinity around the drip line increased as the salinity of the irrigation water increased.
● Very high irrigation efficiencies under drip irrigation can only be obtained by substantial deficit irrigation. This contrasts the assumption frequently made that drip irrigation is nearly 100% efficient for water applications equal to about 100% of the potential evapotranspiration.

The key factor for sustainable drip irrigation is profitability through adequate salinity control. Based on these experiments and simulations, recommended practices for sustainable subsurface drip irrigation of processing tomatoes under saline, shallow ground water conditions include:

● Seasonal water applications should be about equal to the seasonal crop water use. This water application appears to provide sufficient localized leaching. Higher applications could cause ground water intrusion into the root zone; smaller applications will decrease tomato yield.
● Salinity of the irrigation water should be equal to or smaller than about 1 dS m^{-1}.
● Daily to two to three irrigations per week should occur. High frequency irrigations will minimize root uptake of the saline ground water.
● Periodic leaching of salt accumulated above the buried drip lines will be necessary with sprinklers for stand establishment if winter and spring rainfall is insufficient to leach these salts.
● Drip irrigation systems must be designed for high field-wide uniformity of applied water.
● Periodic system maintenance must be performed to prevent clogging of drip lines.

Can drip irrigation eliminate the need for subsurface drainage systems and drainage water disposal methods? No subsurface drainage systems were used at these sites, and no trend in yield with water table depth or soil salinity occurred. Subsurface drip irrigation continues to be used at this time at these sites along with many other fields along the west side.

Little response of the water table to drip irrigation occurred at these sites except at one site where overirrigation occurred early in the year for one year. Reducing the applied water at this site caused the water table to decline. Although drainage below the root zone occurred under subsurface drip irrigation, as shown by the simulations, the amount of drainage per irrigation was small because of the small water applications per irrigation, and because of the high irrigation frequency, its distribution over time was relatively uniform. As a result, the natural subsurface drainage in these fields appeared to be sufficient to prevent ground water intrusion into the root zone. This behavior suggests that, for the conditions found in these fields, subsurface drainage systems and drainage water disposal methods are not needed for properly managed and designed drip irrigation systems. For locations where the water table is affected by drip irrigation, subsurface drainage systems and disposal methods may be required.

REFERENCES

Ayers, R.S., Westcott, D.W. 1985. Water quality for agriculture. Irrigation and Drainage Paper No. 29, Rev. 1. FAO, United Nations. Rome, Italy.

Fulton, A.E., Oster J.D., Hanson, B.R., Phene, C.J., & Goldhamer, D.A. 1991. Reducing drain water: furrow vs. subsurface drip irrigation. *California Agriculture* 45(2): 4-8.

Gärdenäs, A., Hopmans, J.W., Hanson, B.R., Šimůnek J., 2005. Two-dimensional modeling of Nitrate Leaching for Different Fertigation Strategies under Micro-Irrigation. *Agricultural Water Management* 74: 219-242.

Hanson, B.R., Ayars, J.E. 2002. Strategies for reducing subsurface drainage in irrigated agriculture through improved irrigation. *Irrigation and Drainage Systems* 16: 261-277.

Hanson, B.R., Hutmacher, R.B., D.M. May. 2006. Drip irrigation of tomato and cotton under shallow saline ground water conditions. *Irrigation and Drainage Systems* 20: 155-175.

Hanson B.R., May D.M. 2004. Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability. *Agricultural Water Management* 68: 1-17.

Hanson, B.R., Šimůnek, J., Hopmans, J. 2006. Numerical Modeling of Urea-Ammonium-Nitrate Fertigation under Microirrigation. *Agricultural Water Management* 86: 102-113.

Maas, E. V. and S. R. Grattan. 1999. Crop yields as affected by salinity. In R. W. Skaggs and J. van Schilfgaarde (eds) Agricultural Drainage. Agron. Monograph 38. ASA, CSSA, SSA, Madison, WI pp. 55-108

Schoups, G., Hopmans, J.W., Young, C.A., Vrugt, J.A., Wallender, W.W., Tanji, K.K., Panday, S. 2005. Sustainability of irrigated agriculture in the San Joaquin Valley, California. Proceedings of the National Academy of Sciences of the United States of America 102(43): 15352-15356.

Styles, S., Oster, J.D., Bernaxconi, P., Fulton, A., Phene, C. 1997. Demonstration of emerging technologies. In: Agroecosystems: Sources, Control and Remediation, ed. J. Guitjens & L. Dudley, Pacific Division, American Association for the Advancement of Science, San Francisco: 183-206.

WATER RETENTION, COMPACTION AND BEAN YIELD IN DIFFERENT SOIL MANAGEMENTS UNDER A CENTER PIVOT SYSTEM

João Carlos Cury Saad[1]
Leonardo Pretto de Azevedo[2]
Marcelo Augusto de Aguiar e Silva[3]

ABSTRACT

The southwestern region of the state of São Paulo, Brazil presents significant area of annual cultures basically composed of cereals under central pivot system irrigation. The bean culture is part of crop rotation used by irrigators from this region, who perform no-tillage management as a form of sustainable soil use. The objective of this work was to compare two soil management systems: conventional management and no-tillage management systems in relation to their effects on the soil physical-hydric properties, compaction and production components of bean culture under central pivot system irrigation. The experiment was conducted at the Buriti-Mirim Farm, Km 223.5 of the Raposo Tavares Highway, Angatuba, SP, Brazil, during the second semester of 2003 using an area irrigated through center pivot system divided into two types of soil managements: conventional management and no-tillage management. Although no-tillage management presented higher water retention capacity at the most superficial soil layers as well as lower compaction, the soil managements did not present significant differences in relation to culture productivity. Since conservationist management cycles are short, it was verified that the no-tillage management practice generated indirect benefits; however, time was not enough to promote structural changes in the soil and hence significant alterations in the physical-hydric properties that would lead to higher root development and culture productivity.

Keywords: no-tillage management, productivity, available water, central pivot.

INTRODUCTION AND BACKGROUND

Soil Management

In natural conditions, soil is found in a stable state in relation to the environment; however, inadequate management leads to degradation especially of the organic fraction, thus compromising the sustainability of agricultural systems (Gonçalves & Ceretta, 1999). The structure of an ideal soil allows adequate contact area between roots and soil, a continuous, porous and sufficient space for the movement of water and gases and soil resistance to penetration that would not limit the root growth (Koppi & Douglas, 1991).

[1] Professor, Agricultural Science School, São Paulo State University, Rua José Barbosa de Barros, 1780, Botucatu, SP, 18610-307, Brazil; joaosaad@fca.unesp.br
[2] Professor, Agricultural Science School, São Paulo State University, Rua José Barbosa de Barros, 1780, Botucatu, SP, 18610-307, Brazil; pretto@fca.unesp.br
[3] Professor, Agricultural Science School, São Paulo State University, Rua José Barbosa de Barros, 1780, Botucatu, SP, 18610-307, Brazil; aguiaresilva@fca.unesp.br

Due to soil management, the soil is passible both of degradation and of improvement of the productive potential. The different management systems cause alterations on the soil density and porosity and hence on the water storage along its profile, directly influencing the development of the root system and culture productivity. The magnitude of these alterations is a function of the management system adoption time, type of soil and climate of the region. The management systems must adapt to edaphoclimatic, social and regional cultural conditions and contribute for the maintenance or improvement of the soil and environment quality as well as for the attainment of adequate productivity along the years (Costa et al., 2003).

Conventional Soil Management

The conventional soil management is a set of operations performed before sowing with the objective of revolving the soil in order to provide the best physical, chemical and biological conditions for the seed to germinate, besides incorporating fertilizers, correctives and remainders of previous cultures; this latter, as a way to control weeds (Folle & Seixas, 1986). However, the use of this practice for successive years, besides causing excessive physical disintegration and superficial soil management (0.12 to 0.15m), it may also lead to the formation of an impermeable layer underneath the soil surface, known as “grid foot or plow foot” (Freitas, 1992; Fornasieri Filho & Fornasieri, 1993).

No tillage soil management

The conventional soil management has been successfully replaced in many agricultural regions worldwide and particularly in Brazil. In the last decades, the quick degradation of soil under agricultural exploitation worldwide, especially in tropical developing countries has arisen the concern on soil quality and sustainability of the agricultural exploitation (Lal & Pirce, 1991). If intensive tillage is responsible for the soil deterioration, its reduction and the accumulation of organic residues at the soil surface could probably change this condition (Silveira neto et al., 2006). The no-tillage technique has been recommended as alternative to avoid the undesirable effects of inadequate and repetitive soil preparation when intensive tillage practices are used (Chan et al., 1992).

The no-tillage system presents as main characteristic the implementation of culture without drastic soil mobilization, in other words, without its preparation or mobilization before sowing, the mobilization occurs only at the sowing line. This type of system also involves the maintenance of vegetal residues from previous cultures at its surface and the diversification of species through culture rotation. According to Seixas et al. (2005), this culture rotation consists of the alternation of vegetal species at the same area and season, where a minimum period of time is observed without the cultivation of the same species.

Soil compaction

The soil compaction consists of the alteration on its structure, generally caused by the traffic of machines and agricultural accessories or by degradation caused by management and tillage operations. The soil compaction is a process in which porosity and permeability are reduced with impaired structural arrangement, gases diffusion, water infiltration and storage and increased soil resistance to penetration (Taylor & Brar, 1991; Soane & Ouwerkerk, 1994). The soil compaction leads to lower agricultural productivity, once it reduces the soil permeability to air and water and makes root penetration difficult (Lanças et al., 1990; Novak et al., 1992; Freitas, 1994; Pedrotti et al., 1998). In this context, the compacted soil presents lower hydric and nutritional availability, resulting in a thin layer to be explored by the root system.

The conventional soil management, which presents intense mechanization, worsens the soil compaction problems, and this effect is more evident in annual cultures due to the intense soil mobilization during management operations (Silva et al., 1986).

In the no-tillage system, the sowing is performed under remainders of the previous culture, and the surface layers of the soil profile, when compared to the conventional soil management, generally present higher structural stability, higher density and microporosity values and lower macroporosity and total porosity values after three to four years (Vieira, 1981; Vieira & Muzilli, 1984; Corrêa, 1985). This is mainly due to the non-revolving of the soil and to the pressure from the traffic of machines and agricultural accessories, above all when performed in clayish soils with high water contents (Vieira & Muzilli, 1984; Stone & Silveira, 1999). The traffic of heavy machines in the no-tillage system has caused superficial soil compaction (Silva et al., 2000) and reduced culture productivity (Beutler & Centurion, 2003).

One of the indicatives of soil compaction levels is its density (Mantovani, 1987; Reichardt, 1990; Diaz-Zorita, 2000; Queiroz-Voltan et al., 2000). When the system is correctly managed, with good dead coverage and adequate culture rotation, its density may decrease along the years due to the increase on the organic matter content at the superficial layer, also improving the soil structure (Reeves, 1995; Stone & Silveira, 2001), which will promote the fixation of canals that allow adequate air flow and higher water infiltration rates (Seixas et al.,2005).

The soil cone index may be used as an adequate parameter for the characterization of the soil physical-mechanical conditions and estimations of the soil-machine (trafficability, compaction and soil management methods) and soil-root (mechanical hindrance, growth restrictions) interactions, according to Machado et al. (1999). This index is defined as the soil resistance to the penetration of a conical tip and is expressed as the power per area unit of the cone base up to a given depth (Cunha et al., 2002).

Tormena et al. (1998) and Silva et al. (2002) agree that a soil resistance to penetration value of 2000kPa has been associated to unfavorable conditions for the growth of roots and aerial parts of cultures in general. Canarache (1990) and Mertto & Mundstock, (1999) report that values of mechanical resistance to penetration values ranging from 1000 to 3500 kPa may restrict or even hinder the growth and development of roots.

For the bean culture, mechanical resistance to penetration values ranging from 1290 to 2870 kPa do not restrict the grain yield, according to (Carvalho et al. 2006).

Water retention in the soil

Although the soil management under no-tillage increases the soil density and the root penetration resistance, it also increases the volume of stored water available to plants (Klein & Libardi, 1998). The higher water availability in the no-tillage system is associated to the non-revolving of the soil, its lower temperature and larger amount of superficial dead coverage (Vieira, 1984), which reduces evaporation, increases transpiration and hence increases the culture productivity. The maintenance of residues at the soil surface in the no-tillage system, besides the increase on the water retention, also provides higher protection against the direct rain impact (Igue, 1984). The non-revolving of the soil leads to slower and progressive decomposition of the organic matter, thus contributing for the soil and water conservation, also promoting the improvement of its structure that favors aeration and water infiltration, enabling better penetration of the root system (Igue, 1984; Lal, 1986).

A number of works have demonstrated the occurrence of higher water retention under low tensions for soils under no-tillage or minimum tillage (Igue, 1984; Vieira, 1984; Lal, 1986; Salton & Mielniczuk, 1995; Klein & Libardi, 1998; Stone & Silveira, 1999; Stone & Moreira, 2000; Stone & Moreira, 2001). At lower tensions, the pores size distribution is strongly correlated with the water storage. Thus, management systems that cause higher revolving of the soil and therefore higher volume, also store less water at the revolved layer in relation to other identical not revolved layers (Stone & Moreira, 2000).

Objectives

The objective of this work was to evaluate how two different soil management systems, conventional and no-tillage managements, influence the soil water retention, compaction and yield of bean irrigated through central pivot system.

MATERIAL AND METHODS

The study was conducted at the farm of an irrigating producer in the largest irrigated region of the state of São Paulo, Brazil, during the second semester of 2003. The culture selected was bean cultivar Rubi, which sowing occurred at August 02 and harvest at November 25, summing up 116 days of culture cycle.

The experimental design was fully randomized with two treatments and 13 repetitions.

The experimental parcels were placed under an 18 ha central pivot and divided into two soil management types: conventional management (14.4 ha) and no-tillage management (3.6 ha). The conventional management was performed by means of the use of plow and grid, while the no-tillage management was characterized by sowing performed under remainders of the previous culture with no soil revolving. The denomination no-tillage management was used because the parcel with no soil revolving does not characterize a continuous no-tillage system, once operations such as soil preparation aimed at eliminating the cotton stump and sobsoiling for the elimination of compacted soil layers and redistribution of nutrients along the soil profile are periodically performed (Table 1).

Table 1. Culture rotation according to the management program

2001		2002		2003	
1st semester	2nd semester	1st semester	2nd semester	1st semester	2nd semester
Cotton/ oat	Corn	Bean/ oat	Cotton	Oat	Bean

Before the experiment was installed, soil non-deformed samples were collected with the aid of volumetric rings at layers of 0-5cm, 5-10cm, 10-20cm and 20-40cm in both soil management conditions for the attainment of water retention characteristic curves. In order to adjust the pairs of data in relation to soil water tension and the corresponding volumetric humidity, the non-linear equation proposed by Van Genuchten (1980) was used, which parameters were obtained using the Soil Water Retention Curve – SWRC software (Dourado Neto et al., 1990).

Irrigation was monitored by means of three tensiometer batteries in each soil management treatment: conventional management and no-tillage management. Each battery was composed of two tensiometers installed at 15 and 30 cm of depth, where the first one defined the irrigation moment and the second one was used to control the amount of water applied (Saad & Libardi, 1992). The irrigations were performed whenever the average value read in tensiometer placed at 15 cm of depth reached 35 kPa (Silveira & Stone, 1994; Moreira et al., 1999). For the determination of the soil cone index (soil mechanical resistance to penetration), a hydraulic-electronic penetrometer according to Lanças & Santos (1998) was used. The hydraulic-electronic penetrometer, assembled on a cart for haulage and application in tractors with hydraulic system, presents a cone with base area of 320 mm^2, solid angle of 30º and soil penetration constant velocity of 30 mm s^{-1} according to ASAE S313.2 (1991). The electronic system presents a data acquisition system (Microloger 23X, Campbell), power sensor (load cell of 10000 N) and depth sensor (rotational potentiometer). The depths used for the determination of the soil cone index were 0-5; 5-10; 10-20 and 20-40cm in both soil management conditions.

On the occasion of the bean culture harvest, 10 sequential plants in pre-determined site in the useful area of each parcel were collected. These plants were led to the laboratory for the determination of the number of pod/plant, number of grains/plant, average number of grains/pod and mass of 100 grains, determined through random collection and weighting of two samples of 100 grains per parcel.

RESULTS AND DISCUSSION

Figure 1 presents precipitations and irrigations that occurred during the bean plant cycle, 333.5 mm and 188.3 mm, respectively. According to Doorenbos & Kassam (1979), the hydric demand of the bean culture with cycle from 60 to 120 days ranges from 300 to 500 mm to reach high productivity.

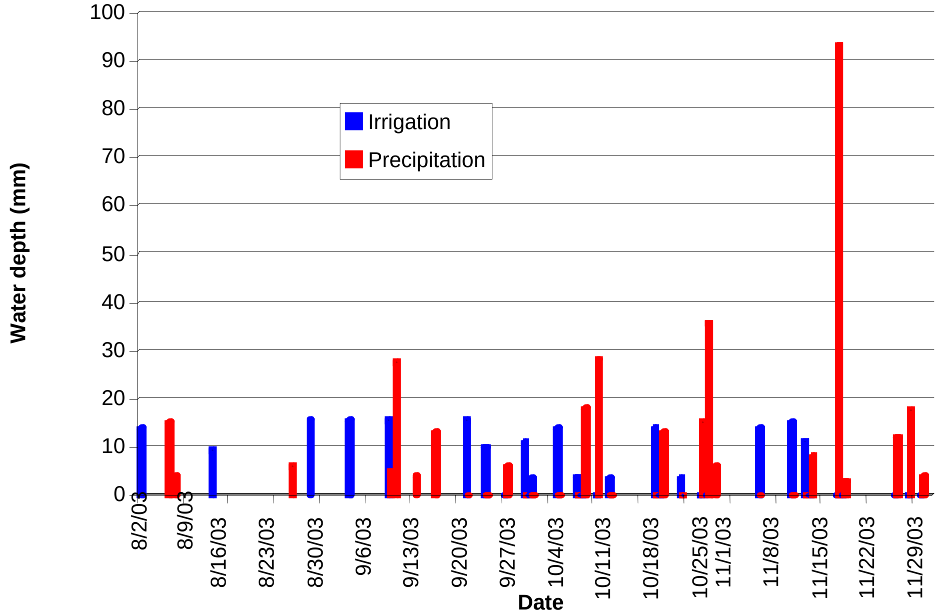


Figure 1. Amount of water x date (irrigation/precipitation). Occurrence of precipitation and irrigation during the bean plant cycle.

In at least two days, 09/09 and 10/20/03, rain precipitation with amount of water equal to or above that applied by irrigation was verified. This evidences the importance of climatic monitoring services that provide information on the probability of rain precipitations, once a slight anticipation on the irrigation or even its suspension could represent water and energy economy and avoid favorable conditions for the development of diseases.

For bean culture, irrigation is recommended when the water tension in soil reaches 35 kPa (Silveira & Stone, 1994; Moreira et al., 1999). In relation to the monitoring of the water tension, Figures 2 and 3 showed a quite similar trend between conventional and no-tillage management conditions. Since the blue line represents the tension equivalent to soil at the field capacity, in other words, 10 kPa and the green line represents the tension of 35 kPa, which indicates the irrigation moment, one observes that in some periods, the tension exceeded these two limits. The periods in which tension was close to 0, in other words, close to saturation, are those corresponding to the occurrence of intense rainfalls (09/10 to 09/16/03).

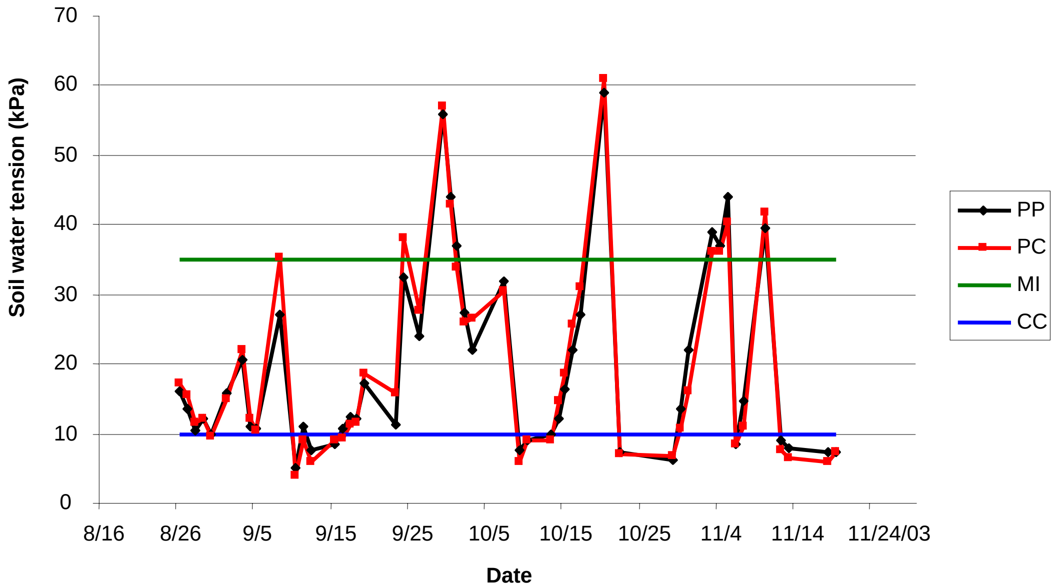


Figure 2. Soil water tension x date. Soil water tension (kPa) at 15cm depth for no-tillage management (DM) and conventional management (CM) conditions, irrigation moment (IM) and field capacity (FC) along the culture cycle.

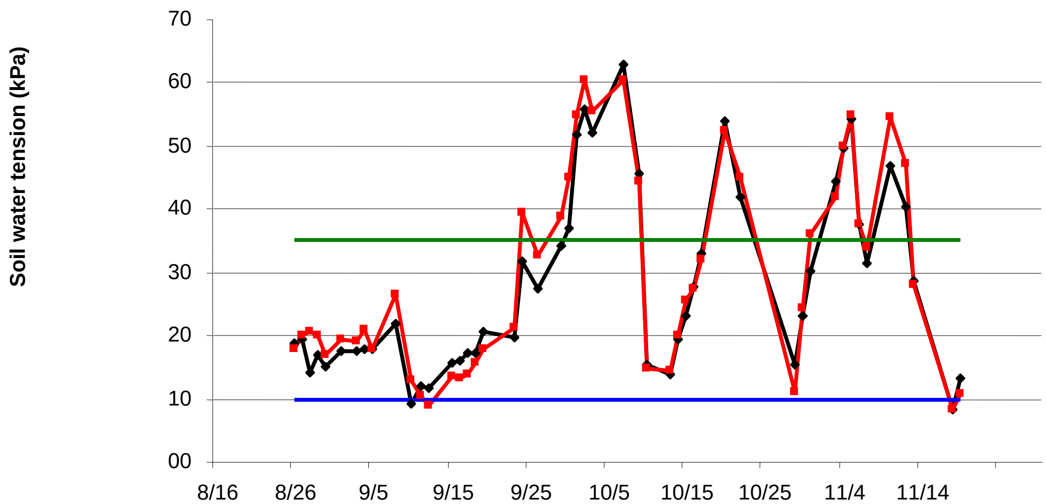


Figure 3. Soil water tension x date. Soil water tension (kPa) at 30cm depth for no-tillage management (DM) and conventional management (CM) conditions, irrigation moment (IM) and field capacity (FC) along the culture cycle.

In some periods, the soil water tension exceeded the limit of 35 kPa, leaving the soil drier with the objective of aiding the control of diseases with high damage potential that diffuse in humid environments such as the white mould.

In identical irrigation and precipitation conditions, no-tillage soil management presented higher amount of water available at the most superficial layers (0 to 5cm and 5 to 10cm), identical values at layer from 10 to 20 cm and lower amount of water at the deepest layer (20 to 40 cm), as shown in Table 2. Higher water availability in no-tillage management at the soil layer from 0 to 10 cm was observed by Urchei (1996), who also observed that in soil layers from 10 to 20 cm and from 20 to 30 cm, both types of soil management conditions presented approximately the same water storage. Considering the effective depth of the bean plant root system ranging from 20 to 30 cm (Moreira, 1993; Stone, 2002), the no-tillage management condition seemed to be more effective for water retention up to this depth and hence there may be more water available to plants and lower variation on its content, once the dead coverage in this condition reduces the water losses due to evaporation (Stone & Silveira, 1999; Stone & Moreira (2000, 2001). Other works (Castro et al., 1987; Salton & Mielniczuk, 1995; Klein & Libardi, 1998) have verified that in no-tillage systems or systems with minimum management in which soil is little revolved or not revolved at all, a higher water retention is observed. According to Vieira (1984), the higher water availability in no-tillage system is associated to the soil non-revolving, lower temperature and larger amounts of superficial dead coverage, which increased the surface rugosity and favored higher infiltration rates.

Thus, plants belonging to no-tillage management presented potential conditions of higher root development and hence higher vegetative growth, higher number of flowers and higher grain yield.

Table 2. Field capacity (FC) in $cm^3\ cm^{-3}$, permanent wilting point (PWP) in $cm^3\ cm^{-3}$, available water (AW) in $mm\ cm^{-1}$, density (Ds) in $g\ cm^{-3}$ and texture at different soil layers for conventional (CM) and no-tillage (DM) management systems.

Soil management	Layer (cm)	FC ($cm^3\ cm^{-3}$)	PWP ($cm^3\ cm^{-3}$)	AW ($mm\ cm^{-1}$)	Ds ($g\ cm^{-3}$)	Texture
CM	0-5	0.3215	0.2764	0.5	1.48	clay
	5-10	0.3172	0.2584	0.6	1.41	clay
	10-20	0.3248	0.2697	0.6	1.41	clay
	20-40	0.3071	0.2418	0.7	1.26	clay
DM	0-5	0.3387	0.2653	0.7	1.23	clay
	5-10	0.3645	0.2934	0.7	1.37	clay
	10-20	0.3885	0.3302	0.6	1.41	clay
	20-40	0.3672	0.3152	0.5	1.36	clay

Since intense mechanization was observed in the conventional management condition, in other words, more traffic of machines, the more superficial soil layers (0 to 5 cm and 5 to 10cm) presented higher density values, according to results presented by Silva et al., 1986; Campos et al., 1995. Since the soil density is the most common form to quantify its compaction (Mantovani, 1987; Reichardt, 1990), one may conclude that up to depth of 10 cm, the no-tillage management was found less compacted. The soil non-revolving and the lower movement of machines and agricultural accessories, in addition to the effect of the dead coverage that increased the organic matter content, provided an improvement on the soil structure at this depth, thus increasing its aggregates and decreasing its density, what contributes for a higher water storage at this condition, according to results found by Stone & Moreira (2000, 2001). Similarly for the available water, at layer of 10 – 20 cm, both soil managements presented the same density, and the deepest layer (20-40 cm) was the conventional management condition that presented the lowest soil density.

The soil cone index is an indirect measurement of soil resistance to root penetration, which presented increase trend up to depth of 20 cm with maximum values of 3254 kPa and 3310 kPa at layers of 10 and 20 cm for no-tillage and conventional management conditions, respectively (Table 3). Comparatively, the conventional management presented higher soil cone index values for layers of 5-10, 10-20 and 20-40cm, and only at layer of 0-5 cm, this value was below that found for no-tillage management.

Table 3. Soil cone index (kPa) for no-tillage management (DM) and conventional management (CM) conditions at the different soil layers.

Soil management	0-5cm	5-10cm	10-20cm	20-40cm
DM	1104	2736	3254	2335
CM	1095	3161	3310	2702

Layers of 5-10 cm and 10-20 cm in conventional soil management present values quite close to each other, 3161 kPa and 3310 kPa, respectively, what may be due to adjustment problems of the agricultural accessories work effective depth, thus evidencing alterations at the depth of the compacted sub-superficial layer.

Physical-hydric alterations at the most superficial layers in the no-tillage management were not sufficient to influence the bean plant production and productivity components favorably, and do not present difference statistically significant at 5% of probability in relation to the conventional management (Table 4). Even though in the no-tillage management condition, plants have produced a higher number of grains, their mass was lower, what resulted in close productivities.

Table 4. Number of grains per plant, number of grains per pod, mass of 100 grains and bean plant productivity for both soil managements.

Soil management	Number of grains per plant	Number of pods per plant	Number of grains per pod	Mass of 100 grains (g)	Bean Yield (Kg ha^{-1})
No-tillage management	83.48a	15.22a	5.14a	18.02a	3360a
Conventional management	78.41a	16.22a	5.16a	19.47a	3330a

Mullins et al. (1980) and Zaffaroni et al. (1991) also reported differences in bean plant yield between no-tillage and conventional soil management. According to Lopes et al. (2004), in the first years of no-tillage and conventional management, it was not possible verifying significant productivity differences between both management systems. However, Stone (2002) concluded that the bean plant yield under no-tillage system increases with the adoption time of this system.

CONCLUSIONS

Up to the depth of 10 cm, the no-tillage system presented lower soil density value, lower compaction and higher water storage capacity in relation to the conventional management. However, these soil management systems presented no significant differences for bean plant yield and for the other production components evaluated.

REFERENCES

ASAE Standard ASAE S313.2, *Soil Cone Penetrometer,* Agricultural Engineers Yearbook of Standards, American Society of Agricultural Engineers, St. Joseph, Michigan, EUA, 591 p., 1991.

Beutler, A.N.; Centurion, J.F. Compactação do solo no desenvolvimento radicular e na produtividade da soja. Pesquisa Agropecuária Brasileira, v.39, 2004. p. 581-588.

Campos, R.C.; Reinert, D.J.; Nicolodi, R.; Ruedell, J.& Petrere, C. Estabilidade estrutural de um Latossolo Vermelho-Escuro distrófico após sete anos de rotação de culturas e sistemas de manejo do solo. Revista Brasileira de Ciências do Solo, v.19, p.121-126, 1995.

Canarache, A. Penetr-a generalized semi-empirical model estimating soil resistence to penetration. Soil & Tillage Research, Amsterdam, v.16, 1990. p. 51-70.

Carvalho, G. J., Carvalho, M. P., Freddi, O. S., Martins, M. V. Correlação da produtividade do feijão com a resistência à penetração do solo sob plantio direto. Revista Brasileira de Engenharia Agrícola e Ambiental, v.10, n.3, 2006. p. 765–771.

Chan, K.Y.; Roberts, W.P.; Heeman, O.F. Organic carbon and associated soil properties of a red earth after 10 years of rotation under different stubble and tillage practices. Australian Journal of Soil Research, Melbourne, v.30, 1992. p. 71-83.

Corrêa, J.C. Efeito de métodos de cultivo em algumas propriedades físicas em um Latossolo Amarelo muito argiloso do Estado do Amazonas. Pesquisa Agropecuária Brasileira, Brasília, v.20, n.11, 1985. p. 1317-1322.

Costa, F.S.; Albuquerque, J.A.; Bayer, C.; Fontoura, S.M.V.; Wobeto, C. Propriedades físicas de um Latossolo Bruno afetadas pelos sistemas plantio direto e preparo convencional. **Revista** Brasileira de Ciências do Solo**,** v.27, 2003. p. 527-535.

Cunha, J.P.A.R.; Vieira, L.B.; Magalhães, A.C. Resistência Mecânica do Solo à Penetração Sob Diferentes Densidades e Teores de Água. Engenharia na Agricultura, v.10, n.1-4, 2002.

Díaz-Zorita, M. Effect of deep-tillage and nitrogen fertization interactions on dryland corn (*Zea mays* L.) productivity. Soil & Tillage Research, Amsterdam, v. 54, 2000. p. 11-19.

Doorenbos, J; Kassam, A.H. Yield response to water**.** Rome: FAO, 1979. 193p. (FAO, Irrigation and Drainage Paper 33).

Dourado Neto, D., Lier, Q.J.V.; Botrel, T.A., Libardi, P.L. Programa para confecção da curva característica de retenção de água no solo utilizando o modelo de Genuchten. Engenharia Rural, v.1, n.2, p.94-101, 1990.

Folle, S.M.; Seixas, J.M. Mecanização agrícola. In:GOEDERT, W.J. (Ed). Solos dos cerrados: tecnologias e estratégias de manejo. São Paulo: NOBEL/EMBRAPA CPAC, 1986, p.385-408.

Fornasieri Filho, D.; Fornasieri, J.L. Manual da cultura de arroz**.** Jaboticabal: Funep, 1993. 221 p.

Freitas, P.L. Manejo físico do solo. In: SIMPÓSIO SOBRE MANEJO E CONSERVAÇÃO DO SOLO NO CERRADO, 1., 1990, Goiânia. Anais**.** Campinas: Fundação Cargill, 1992. p. 117-139.

Freitas, P.L., de. Aspectos físicos e biológicos do solo. In: LANDERS, J.N. (Ed). Experiências de plantio direto no Cerrado**.** Goiânia: APDC, 1994. p.199-213.

Gonçalves, C.N., Ceretta, C.A. Plantas de cobertura de solo antecedendo o milho e seu efeito sobre o carbono orgânico do solo, sob plantio direto. Revista Brasileira de Ciências do Solo**,** Viçosa (MG), v.23, n.2, 1999. p. 307-313.

Igue, K. Dinâmica da matéria orgânica e seus efeitos nas propriedades do solo. In: ADUBAÇÃO VERDE NO BRASIL. Campinas: Fundação Cargill, 1984. p.232-267.

Klein, V.A., Libardi, P.L. Armazenagem de água no solo e resistência à penetração. In: REUNIÃO BRASILEIRA DE MANEJO E CONSERVAÇÃO DO SOLO E DA ÁGUA, 12.

1998. Fortaleza/Ceará.. Sociedade Brasileira Ciências do Solo. Universidade Federal do Ceará. 1998. p.163-164.

Koppi, A.J.; Douglas, J.T. A rapid inexpensive and quantitative procedure for assessing soil structure with respect to cropping, v.7, 1991. p. 52-56.

Lal, R.; Pirce, F. J. The vanishing resource. *In*: LAL, R.; PIRCE, F. J. (Ed.). Soil managment for sustainability. Ankeny: Soil and Water Conservation Society, 1991. p. 1-5.

Lanças, K.P., Benez, S.H., Furlani Jr, J.A., Gamero, C.A., Antuniassi, U.R. Subsolador: desgaste em função da sua dureza superficial. In: Congresso Brasileiro de Engenharia Agrícola, 19., Piracicaba, SP. 1990**.** Anais**.** Piracicaba, SP. 1990. p. 801-809.

Lanças, K. P., Santos Filho, C.A. Penetrômetro hidráulico-eletrônico equipado com DGPS para avaliação da compactação do solo**.** La Plata, Editorial de la U.N.L.P. p. 570-576. 1998.

Machado, A.L.T., Trein, C.R., Bica, A.V.D., Boeni, M. Desenvolvimento e aplicação de um penetrógrafo eletrônico. In: CONGRESSO BRASILEIRO DE ENGENHARIA AGRICOLA, 28, A Engenharia Agrícola – TENDÊNCIAS E INOVAÇÕES. 1999, Pelotas, RS, Anais**...** Pelotas/RS, (CD ROM). 1999.

Mantovani, E.C. Compactação do solo. Informe Agropecuário**,** Belo Horizonte, v.13(147), 1987. p. 52-55.

Merotto, A. & Mundstock, C.M. Wheat root growth as affected by soil strength. Revista Brasileira de Ciência do Solo, v.23, 1999. p. 197-202.

Moreira, J.A.A., Stone, L.F., Silva, S.C., Silveira, P.M. Irrigação do feijoeiro no sistema plantio direto. Santo Antônio de Goiás: Embrapa Arroz e Feijão, p. 31, 1999. (Embrapa Arroz e Feijão. Circular Técnico, 33).

Mullins, C.A.; Tompkins, F.D.; Parks, W.L. Effects of tillage methods on soil nutrient distribution, plant nutrient absorption, stand, and yield of snap beans and lima beans. Journal of the American Society of Horticultural Science, Alexandria, v.105, 1980. p. 591-593.

Novak, L.R., Mantovani, E.C., Martyn, P.J., Fernandes, B. Efeito do tráfego de trator e da pressão contato pneu/solo na compactação de um Latossolo Vermelho-Escuro álico, em dois níveis de umidade. Pesquisa Agropecuária Brasileira**,** Brasília, v.27, 1992. p. 1587-1595.

Pedrotti, A., Vahl, L.C., Pauletto, E.A. Níveis de compactação do planossolo e o desenvolvimento radicular de algumas culturas. In: REUNIÃO BRASILEIRA DE MANEJO E CONSERVAÇÃO DO SOLO E DA ÁGUA, 12. 1998. Fortaleza/Ceará. Resumos expandidos**.** Sociedade Brasileira Ciências do Solo. Universidade Federal do Ceará. 1998. p. 89-90.

Queiroz-Voltan, R.B.; Nogueira, S.S.S.; Miranda, M.A.C. Aspectos da estrutura da raiz e do desenvolvimento de plantas de soja em solos compactados. Pesquisa Agropecuária Brasileira, v.35, 2000. p. 929-938.

Reeves, D.W. Soil management under no-tillage: soil physical aspects. In: SEMINIRIO INTERNACIONAL DO SISTEMA PLANTIO DIRETO, 1., 1995, Passo Fundo. Resumos. Passo Fundo: Embrapa-CNPT, 1995. p. 127-130.

Reichardt, K. **A** Água em Sistemas Agrícolas**.** Barueri, SP: Manole, 1990.

Saad, A.M.; Libardi, P.L. Uso prático do tensiômetro para o irrigante**.** São Paulo: IPT, 1992. 27 p. (IPT. Comunicação Técnica).

Salton, J.C.; Mielniczuk, J. Relações entre sistemas de preparo, temperatura e umidade de um Podzólico Vermelho Escuro de Eldorado do Sul (RS). Revista Brasileira de Ciência do Solo, v.19, 1995. p. 313-319.

Seixas, J.; Roloff, G.; Ralish, R. Tráfego de máquinas e enraizamento do milho em plantio direto. Ciência Rural, Santa Maria, v.35, n.4, 2005. p. 794-798.

Silva, A.P., Libardi, P.L., Camargo, O.A. Influência da compactação nas propriedades físicas de dois Latossolos. Revista Brasileira de Ciência do Solo**,** v.10, 1986. p. 91-95.

Silva, V.R.; Reinert, D.J.; Reichert, J.M. Resistência mecânica do solo à penetração influenciada pelo tráfego de uma colhedora em dois sistemas de manejo do solo. Ciência Rural, v.30, 2000. p. 795-801.

Silva, A. P.; Tormena, C. A.; Imhoff, S. Intervalo hídrico ótimo. In: MORAES, M. H.; MÜLLER, M. M. L.; FOLONI, J. S. S. Qualidade física do solo: métodos de estudo-sistemas de preparo e manejo do solo. Jaboticabal: Funep, 2002. p. 1-18.

Silveira, P.M.; Stone, L. F. Manejo da irrigação do feijoeiro: uso do tensiômetro e avaliação do desempenho do pivô central**.** Goiânia: EMBRAPA, p.46 1994. (Circular Técnico, 27).

Silveira Neto, A. N., Silveira, P. M., Stone, L. F., Oliveira, L. F. C. Efeito de manejo e rotação de culturas em atributos físicos do solo. Pesquisa Agropecuária Tropical, v.36, n.1, 2006. p. 29-35.

Soane, B.D. & Ouwerkerk, C. van. Soil compaction problems in world agriculture. In: SOANE, B.D. & OUWERKERK, C. van, eds. Soil compaction in crop production. Netherlands, Elsevier,. p.01-21. 1994.

Stone, L. F. Efeito de lâminas de irrigação e preparo do solo na resposta do feijoeiro ao nitrogênio em cobertura**.** Santo Antônio de Goiás: Embrapa Arroz e Feijão, 2002. 24p.

Stone, L. F.; Moreira, J.A.A. Efeito de sistemas de preparo do solo no uso da água e na produtividade do feijoeiro. Pesquisa Agropecuária Brasileira**,** v.35, n.4, 2000. p. 835-841

Stone, L.F.; Moreira, J.A.A. Resposta do feijoeiro ao nitrogênio em cobertura, sob diferentes lâminas de irrigação e preparos do solo**.** Pesquisa Agropecuária Brasileira**,** Brasília, v.36, n.3, 2001. p. 473-481.

Stone, L. F.; Silveira, P. M. Efeito do sistema de preparo na compactação do solo, disponibilidade hídrica e comportamento do feijoeiro. Pesquisa Agropecuária Brasileira**,** v.34, 1999. p. 83-91.

Taylor, H.M.; Brar, G.S. Effect of soil compaction on root development. Soil and Tillage Research, v.19, 1991. p. 111-119.

Tormena, C.A.; Silva, A.P.; Libardi, P.L. Caracterização do intervalo hídrico ótimo de um Latossolo Roxo sob plantio direto. Revista Brasileira de Ciência do Solo, v.22, 1998. p. 573-581.

Urchei, M.A. Efeitos do plantio direto e do preparo convencional sobre alguns atributos fÌsicos de um Latossolo Vermelho-Escuro argiloso e no crescimento e produtividade do feijoeiro (*Phaseolus vulgaris* L.) sob irrigação. Botucatu: UNESP, 1996. 150p. Tese de Doutorado.

Van Genuchten, M. Th. A closed forma equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal**,** Madison, v.44, p.892-898, 1980.

Vieira, M.J. Propriedades físicas do solo. In: IAPAR (Londrina, PR). Plantio Direto no Estado do Paraná**.** Londrina, 1981. p.19-32. (IAPAR. Circular, 23).

Vieira, M.J. O preparo do solo e o comportamento da planta. Plantio Direto, Ponta Grossa, v.1, n.5, 1984. p. 4-5.

Vieira, M.J.; Muzilli, O. Características físicas de um Latossolo Vermelho-Escuro sob diferentes sistemas de manejo. Pesquisa Agropecuária Brasileira, Brasília, v.19, n.7, 1984. p. 873-882.

Zaffaroni, E.; Barrod, H.H.A.; Nobrega, J.A.M.; Lacerda, J.T.; Souza Junior, V.E. Efeito de métodos de preparo do solo na produtividade e outras características agronômicas de milho e feijão no Nordeste do Brasil. Revista Brasileira de Ciência do Solo**.** Campinas, v.15, n.1, 1991. p. 99-104.

PRECISION MECHANICAL MOVE IRRIGATION FOR SMALLHOLDING FARMERS

Jacob LaRue[1]

ABSTRACT

Mechanical move irrigation equipment typically has been designed for square fields 805 m long on each side, as much of the western United States was surveyed and laid out on a township grid system with these field dimensions. Center pivots commonly cover 52.6 hectares out of 64.8 total hectares. Because of this, a common misconception is that mechanical move irrigation equipment such as center pivots and lateral move equipment are only economically viable for large fields. But what about small holding farmers – are there economically viable solutions for them to utilize mechanical move irrigation such as center pivots? What options are commercially available for them to take advantage of the benefits associated with mechanical move irrigation such as precision irrigation, application uniformity, irrigation efficiency and low energy costs? This paper will discuss mechanical move equipment options available for small holding farmers and the infrastructure requirements for this type of equipment. These will be compared to other options a smallholding farmer may be considering for irrigation. Estimated relative costs for project development and operation will be presented for each. Case studies of mechanical move equipment for small fields installed in Asia and Africa will be presented and preliminary results discussed including the 'fit' of this type of equipment into the cultural structure of the area. Based on current data, a proposed economic model to assist with the evaluation of the suitability of mechanical move irrigation for smallholding farmers will be presented. The paper will close with a discussion of future needs and concerns.

INTRODUCTION

When one flies over many parts of the United States, parts of South America and the Middle East, it is common to see large 'circles' on the land below. These are created by mechanized irrigation - specifically the center pivot. Typically these center pivots are about 400 meter in length and cover approximately 50 hectares. The center pivot was invented in the central plains of the United States and by far the largest concentrations of these units are in the southern and central plains of the USA where the land was divided into square blocks of townships, sections and the quarter being the smallest unit – 805 meters x 805 meters. The original center pivot was designed to fit this size of field.

Before the discussion is continued, a summary of the basic components of a center pivot needs to be presented. Typically the center pivot consists of several basic components:

1) Pivot point – which anchors the pivot and about which the center pivot rotates

[1]Manager, Project and Product Support, Valmont Industries International Irrigation, Valley, Nebraska, USA
jlarue@ valmont.com

2) Spans – which carry the water and provide mobility consisting of:
    a. pipeline structure– which carries the water to the water application package
    b. overhang - which extends past the last set of wheels
    c. drive unit/drive train – at the out end of each pipeline section.

3) Water application package – which applies the water in the manner desired by the customer to meet their crop needs

4) Controls – which allow the operator to start, stop, control application depth and control other equipment operations

Every center pivot requires:
1) One pivot point – fixed or towable
2) One control
3) One to twenty two spans
    a. Drive mechanism
4) One water application package

When the center pivot was introduced in the 1950's, the drive train was propelled using water pressure. In the late 1960's three phase electric motors were introduced to provide power to move the drive train. As energy costs rose in the 1970's, the electric drive became the dominate form for providing power.

From the 1950's until the late 1990's the focus continued on center pivots of 400 meters and larger. The center pivot has and continues to bring a variety of significant features to the farmer including uniform application, high efficiency of application, low energy requirements, maximum flexibility of a variety of crops and growing cycles, and minimal filtration requirements. While the general size of 400 meters has worked well in the United States and other countries with large open areas for irrigation, many countries of the world have areas being irrigated by traditional methods which are significantly smaller.

For our discussions, we will consider small holdings farms of one to two hectares.

DISCUSSION

What forms of mechanized irrigation are available to small holding farmers? The same components that are used to make a large center pivot can be used for small holdings.

Equipment options available

A basic drawback for many small fields to utilize center pivots is the lack of three phase power. Three phase power can in many cases prove to be a significant limitation due to the cost and the extensive infrastructure that may be required. To overcome this, center pivot manufacturers offer a number of specific drive train power options for single span center pivots.

Single Span Spinner Drive (Figure 1) –

- Utilizes water pressure to provide the power for the drive train.
- The rest of the drive train is the same as for a conventional center pivot
- Advantage
  - Requires no electric power

- Disadvantages
  - Requires a minimum of 2 bars of water pressure
  - Limited slope capabilities

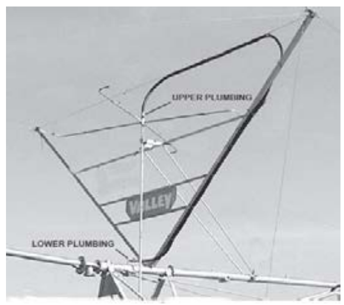


Figure 1. Spinner span drive

Single Span Engine Drive – (Figure 2)

- Utilizes a 4kw internal combustion engine to provide the power for the drive train.
- Advantages
  - Almost no slope limitations
  - Independent of water pressure
  - Easily reversible
- Disadvantages
  - Requires fuel
  - Requires maintenance

Figure 2. Engine span drive

Multi span Electric drive – (Figure 3)

- Utilizes a 0.4kw 480vac motor
- Advantages
    - Almost no slope limitations
    - Operates independently of water pressure
- Disadvantages
    - Requires three phase power source
    - Requires power cable, tower box, collector ring and electric control panel

Figure 3. Electric span drive

Comparison to other irrigation options available for small holdings

Any of these drive options allow the small holding farmer to take advantage of the benefits of center pivots – high application efficiency, high uniformity, flexibility in cropping, and in both of the single span options, simplified infrastructure requirements.

Type	Energy Consumption	Application Uniformity	Cropping Flexibility
Single span mechanical	low	high	high
Surface irrigation	low	low	high
Handmove sprinkler	high	medium	medium
Drip irrigation	low	low	low

Discussion of terms used:

Energy consumption – in general terms it will distinguish if the technology is a high or low user of energy for the amount of irrigation that is used

Application uniformity – in general terms it is the water applied for irrigation that is equally distributed across the entire field

Cropping flexibility – it determines if the type of irrigation has any limitations to the type of crop that can be produced and if the type of irrigation easily allows for a rapid transition between crops

CASE STUDIES – EQUIPMENT AND CULTURAL IMPACT

Case 1 – China

Equipment type used is a Single Span with Spinner drive. The majority use a two wheel EZ Tow pivot point to allow easy movement from one field to the next. A few farms use a fixed pivot point. The span configuration is 60.6m span with a 22.6m overhang covering 2.1ha per set. The machines are towed between two up to six different sets irrigating a total of 4.2 to 12.6ha per unit. The drive train propulsion is water from the impulse arms. There is no control – the unit is either on or off. The water application package is a Senninger I-Wob package.

The crops produced are forage, feed grains and vegetables.

Each machine is shared between three to ten farmers (Figure 4).

The farmers have found the Single Span easy to operate requiring little skill. The Spinner drive provides good uniformity but little control of the depth of water applied per pass. The machine has been simple for them to move from field to field.

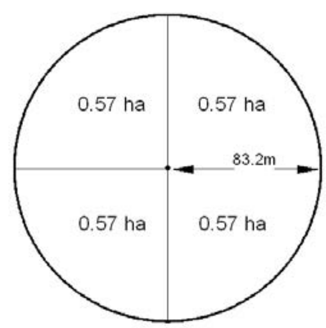


Figure 4

Culturally the Single Span Spinner Drive has fit well and sharing of a single unit by farmers has been readily acceptable.

Case 2 – Pakistan

Equipment type used is a Single Span with Engine drive. The farmers use a two wheel EZ Tow pivot point to allow easy movement from one field to the next. The span configuration is 60.6m span with a 22.6m overhang covering 2.1ha per set. The machines are towed between two up to six different sets irrigating a total of 4.2 to 12.6ha per unit. The drive train propulsion is a 3.7kw gasoline engine. Control is via setting of the throttle of the engine. Water application is provided using a Valley LEN package.

The crops produced are forage and feed grains.

One farmer owns one machine and no units are shared between farmers.

The farmers have found the Single Span Engine Drive easy to operate and allowing control of the depth of water applied per pass. The machine has proved to be simple for them to move from field to field. The Single Span does not require the degree of filtration required for drip systems also used in the area.

Culturally the Single Span Engine Drive has been a good fit and interest exists for a small group of farmers to consider sharing of a unit.

One major issue is the water delivery which impacts all of the precision irrigation solutions. The typical water delivery through the canal system is water is available for seven days and then no water for seven days. This presents a challenge when trying to manage the machine for efficient irrigation.

Case 3 – South Africa

Equipment type used is a Single Span with Spinner drive. The farmers use a two wheel EZ Tow pivot point to allow easy movement from one field to the next. The span configuration is 60.6m span with a 22.6m overhang covering 2.1ha per set. The machines are towed between three to up to eight different sets irrigating a total of 3.6 to 16.8ha per unit. The drive train propulsion is the Spinner impulse arms. No control of water application depth is available since the unit is either on or off. Water application is provided using a Senninger LDN package.

The crops produced are forage, feed grains and vegetables.

One farmer owns one machine and no units are shared between farmers.

The farmers have found the Single Span Spinner Drive simple to operate but does not allow for varying the depth of water applied. Some units are on fields with rolling topography and sufficient water pressure to provide propulsion has been a challenge in some cases.

The Single Span Spinner Drive has seemed to fit well with the culture. Sharing of a unit does appear to be feasible but has not been done at this time.

Economic model of the relationship of initial investment costs to irrigated area

Table 1.
Capital Investment (USD/ha)*

Area (ha)	Spinner	Engine Drive	Drip	Surface	Handmove
2.2	$6,620	$7,265	$5,925	$714	$10,221
4.4	$3,310	$3,633	$4,516	$678	$7,155
6.6	$2,207	$2,422	$4,046	$644	$5,008
8.8	$1,655	$1,816	$3,811	$631	$3,506
11.0	$1,324	$1,453	$3,670	$618	$3,506

Assumptions:

- General assumptions
  - 8.2 liters per second
  - Sufficient pressure for the irrigation package
- Spinner and Engine Drive –
  - Two wheel E-Z Tow pivot point
  - 60.6m, 125mm diameter spans
  - 22.6m overhang
  - 14.9x24 tires
- Drip
  - Drip tape with 34mm spacing
  - Flowrate of 1.5 liters per hour
  - Rows spaced at 1.2 meters
  - Necessary headers but no flush lines
  - Filter system to match flow requirements.
- Surface
  - Assumes some leveling required but not substantial
- Handmove
  - 100mm mainline with 12 meter sprinkler spacing
  - Lines spaced at 18 meters

The Single Span Spinner and Engine Drive are both designed to be easily moved from field to field. With these machines, the initial investment costs decrease as the unit is towed to more fields. There is a limit to the number of fields the units may be effectively towed as determined by the crop water requirements and how quickly one must return to the first field irrigated by the machine. The drip system costs reduce gradually due to the spreading of the filter station costs over more area. Surface irrigation only slightly changes with increased area. Lastly the handmove type of irrigation reduces only to a certain point as it eventually becomes necessary to add more hardware to be able to effectively irrigate the field. For very small areas based strictly on initial investment one sees the least costly would be surface irrigation if one is not water limited. If water is limited, the logical investment would be drip for 2.2 hectare fields.

As field sizes change, so does the capital investment. Surface irrigation will continue to be the least costly initial investment but once one begins to tow a pivot to at least one other set, the

Single Span Spinner or the Single Span Engine Drive become the best choice when water is limited.

The next table presents the annual operating costs associated with each of the forms of irrigation we have discussed.

Table 2.

Annual Operating Expense (USD/ha)

	Spinner	Engine Drive	Drip	Surface	Handmove
Energy Costs	$1,141	$225	$338	$90	$1,217
Maintenance	$82	$118	$139	$178	$160

For the energy costs, pressures are based on typical requirements for the particular type of irrigation. Power is calculated on only the requirement to pressurize the irrigation equipment and a pump efficiency of 75%. Energy costs are assumed to be $ 0.12 per kilowatt.

Maintenance costs are based on estimates for each type of irrigation and experience with each. It includes material and labor. Labor is assumed to be semi skilled and costs $10.00 per day.

When annual operating costs are combined with initial investments the following model emerges.

Table 3.

Combined Annual Cost over a Ten Year Period (USD/ha)

Area (ha)	Spinner	Engine Drive	Drip	Surface	Handmove
2.2	$1,884	$1,070	$957	$340	$2,399
4.4	$1,553	$707	$816	$336	$2,092
6.6	$1,443	$586	$769	$333	$1,878
8.8	$1,388	$526	$745	$332	$1,727
11.0	$1,355	$489	$731	$330	$1,727

Again for the smallest field, the lowest cost solution is surface irrigation if water is not limited. If water is a limiting factor, drip is the best choice. As the area increases, the Single Span Engine Drive becomes the best solution if water is limited and even may approach costs comparable to surface irrigation if one tows the Single Span Engine drive to four different sets.

It is always necessary to continue to improve the products, particularly to better meet the needs of end user. Mechanical move irrigation will continue to provide solutions and innovations to offer the best value to customers of fields of all sizes and a variety of crops. More work needs to be done to utilize alternative fuels in the engine drive package. Maybe ethanol and/or bio-diesel will prove to be viable options. Additionally water delivery system management must be reviewed and understood.

CONCLUSIONS

From the economic model one may draw some conclusions relating to the application of mechanical move irrigation for small holding farmers. One must consider what drives the customer's buying decision. If water is not limited then using traditional surface irrigation methods may be the best economical choice. But if water is limited or could become limited in the future, then one needs to consider other options. These options will be dependent on the field size and to some degree shape. Once one considers towing a mechanical move machine, the costs change quickly and the Single Span Engine Drive becomes the least cost option due to the operating costs of the Single Span Spinner Drive.

In addition one must consider the advantages beyond just the cost for each type of irrigation. The following provides a brief summary.

	Cropping Flexibility	Ability to Manage Soil & Water Chemistry	Application Uniformity
Single span – Spinner	Excellent	Excellent	Excellent
Single span – Engine	Excellent	Excellent	Excellent
Drip irrigation	Fair	Poor	Poor
Surface irrigation	Fair	Fair	Poor
Handmove sprinkler	Good	Good	Fair

REFERENCES

Amosson, S., New, L., Almas, L., Bretz, F., and Marek, T, 2001 Economics of Irrigation Systems, B-6113, Texas Cooperative Extension

Camp, J. (2007) Personal communication

Fidler, B. (2007) Personal communication

Marais, L. (2007) Personal communication

Moss, J., Wolf, G., Gladden, G. and Guttieriez, E., 2003 *Valuing Water for Better Governance*, CEO Panel Business and Industry

O'Brien, D., Rogers, D., Lamm, F., and Clark, G., Economic Comparison of SDI and Center Pivots for Various Field Sizes, Irrigation Management Series, Kansas State University Cooperative Extension Service

Payero, J., Yonts, D., Irmak, S., and Tarkalson, D., 2007, Advantages and Disadvantages of Subsurface Drip Irrigation, EC776, University of Nebraska Extension

WILD FLOOD TO GRADED BORDER IRRIGATION FOR WATER AND ENERGY CONSERVATION IN THE KLAMATH BASIN

Jason Smesrud[1]
Mark Madison[2]

ABSTRACT

A large percentage of pasture in the Upper Klamath Basin is irrigated by “wild flood” surface irrigation methods. Efforts underway to improve irrigation efficiency in the basin using federal funds have included conversions to sprinkler irrigation systems and to higher efficiency graded border surface irrigation systems. With dramatic increases in power rates for agricultural users on the horizon, surface irrigation enhancements have significant promise to increase water use efficiency without substantially increasing production costs. While these projects generally do not solve the basin’s water supply problems, they do provide a significant enhancement to surface water quality by reducing sediment and nutrient containing surface return flows. In areas where groundwater levels are declining due to irrigation pumping, these projects can also reduce stresses on groundwater supplies. A project implemented near Sprague River is used as a case study to describe how the simple conversion from ditched to piped laterals, creation of new border ridges, and improvements to irrigation scheduling can dramatically increase irrigation application efficiency while at the same time reducing pumping costs and groundwater withdrawals without any increase to daily labor requirements.

INTRODUCTION

Competition for water supplies within the Upper Klamath Basin (south-central Oregon) was brought to a head in 2001, when the combination of drought and Endangered Species Act (ESA) water management decisions severely curtailed irrigation deliveries to more than 2,000 farms and ranches. Since that time, a significant amount of federal support has been provided to the region to support water conservation measures. As administered through the Natural Resources Conservation Service (NRCS), the Environmental Qualities Incentive Program (EQIP) is one vehicle that has been used to invest federal funds in improving the irrigation efficiency of operating farms while keeping them in operation and attempting to alleviate some of the stresses on water resources in the basin.

While much of the cost-share funding through EQIP has been focused on converting low efficiency flood irrigation systems to sprinkler systems, some funding has also been directed to convert low efficiency flood irrigation systems to higher efficiency flood irrigation systems. In both cases, the primary benefit of irrigation efficiency enhancements is water quality improvement, as total consumptive use is not normally reduced significantly. In fact, in some cases, the improved uniformity of irrigation application can increase consumptive use following

---

[1] Global Technology Leader for Agricultural Services; CH2M HILL, 2020 SW 4th Ave, Suite 300, Portland, OR 97201; Jason.Smesrud@ch2m.com

[2] Principal Agricultural Engineer; CH2M HILL, 2020 SW 4th Ave, Suite 300, Portland, OR 97201; Mark.Madison@ch2m.com

conservation improvements. The largest direct benefit of these conservation measures is thus the reduction in tailwater return flows to surface water, because tailwater return flows carry nutrients and sediments that negatively impact sensitive receiving waters.

Within the Upper Klamath Basin, the Sprague River Sub-basin has been identified as having the greatest opportunity for irrigation water conservation measures providing significant benefit to basin water quality and reducing ESA constraints (USDA-NRCS, 2004). In this subbasin, irrigation is primarily used for irrigated pasture and grass hay over about 82,000 acres and is predominantly managed with low efficiency flood irrigation practices, locally termed “wild flood.” Approximately 35 percent of irrigation diversions are from groundwater with the remaining 65 percent from streams.

This paper uses a case study of a 100-acre wild flood irrigated pasture located in the Sprague River Sub-basin as an example of the projected water balance and economic impacts of converting a ditched delivery wild flood irrigation system to an engineered piped delivery graded border system. This EQIP funded project was initiated in late 2005 with a participating landowner. It was constructed following the end of the irrigation season in 2006 and commissioned at the start of the 2007 irrigation season.

IRRIGATION SYSTEM DESIGN

Methods for increasing surface irrigation application efficiency include land leveling or smoothing, breaking fields into shorter run lengths, piping or lining ditch delivery systems, decreasing set times, and increasing the level of irrigator management. For this particular project, the methods selected for increasing on-farm application efficiency included the following components:

- Converting the ditch delivery system to a piped delivery system by installing buried PVC piping with alfalfa riser valves on 50-ft spacing. This improvement eliminates the conveyance water loss from ditch seepage and allows greater user control over the locations of water delivery to the field.
- Constructing border ridges on 50-ft to 150-ft spacing with settled heights of at least 4 inches. This measure reduced the average field run length from 1,200-ft to 900-ft between head ditches/laterals and will enable more uniform coverage of the entire field.
- Installation of a pump timer to enable automatic pump shut down at the end of an irrigation set. This eliminates the reliance on an irrigator returning to the field to physically turn off the pump.
- Installation of a flow meter to allow the user to keep track of water application.
- Development of an irrigation water management plan to assist the user in managing irrigations to crop irrigation requirements.

The first step in the design process was a meeting with the landowner to discuss historic irrigation operations, labor limitations for post-project operations, and project goals and to gather necessary design basis information. During this same visit, topographic survey information was collected and a field flood irrigation test was conducted to provide design information (Figure 1). Following the field data collection, the SRFR model (Strelkoff et al., 1998) was used for evaluating pre- and post-project irrigation management to estimate application efficiency, field water balances, and effective set times, and unit flow rates. This step was used to refine the design and operational criteria prior to designing the physical system improvements.

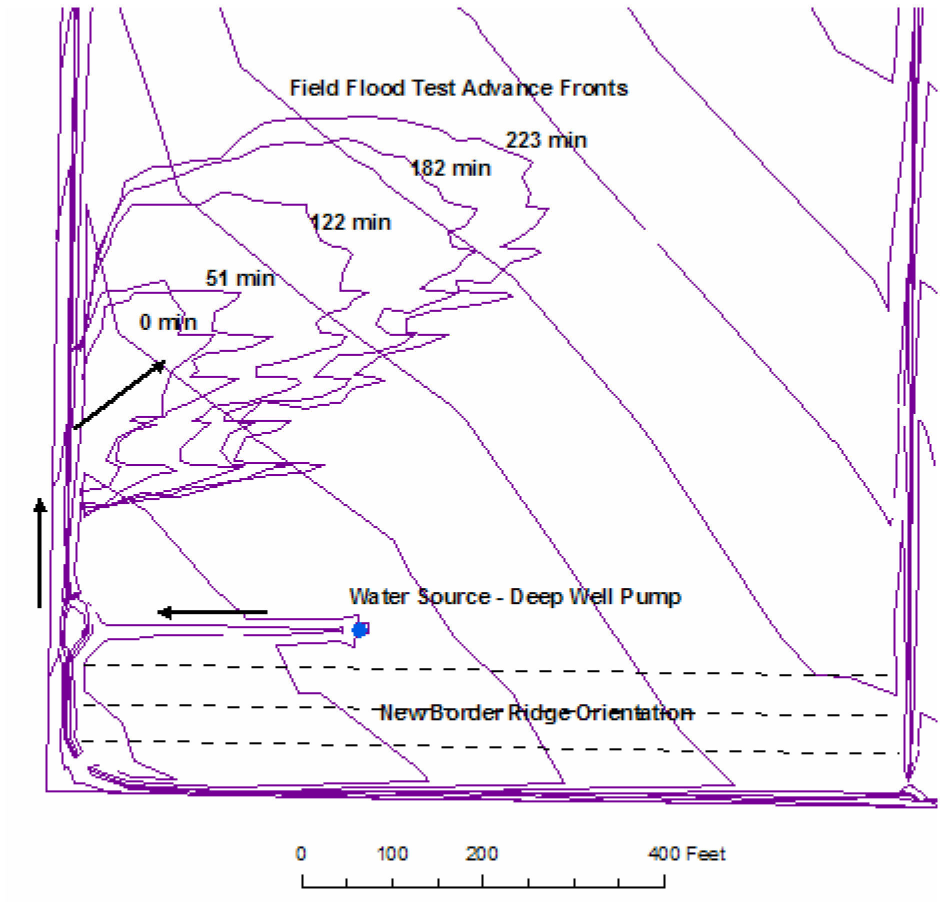


Figure 1. Map of a portion of the 100-acre field where the field flood irrigation test was conducted (contour lines are shown at 1-foot intervals).

During the field flood irrigation test, flood advance fronts were mapped at several intervals over an approximately 4 hour period (Figure 1). The advance fronts in Figure 1 illustrate the current direction of irrigation flows across one of the fields and the planned new border ridge orientation, which will decrease both the field run length and the surface slope along the flow path. Historic border ridges that have long since settled and been reduced to micro-topography from cattle traffic can also be seen in the advance front mapping.

Before running design scenarios, the SRFR model was first calibrated to the field performance data to enable better estimates of soil intake rates and surface roughness parameters. Using the measured flow rates during the test and the advance distances over time, the SCS intake family and Manning n values were adjusted in SRFR until the appropriate advance curve shape and slope were replicated (Figure 2). While this approach may not yield a unique solution to these two parameters (Clemmens et al, 2001), it does provide a reasonable design basis for evaluation of pre- and post-project operations given that the unit flow rates will not be varied significantly.

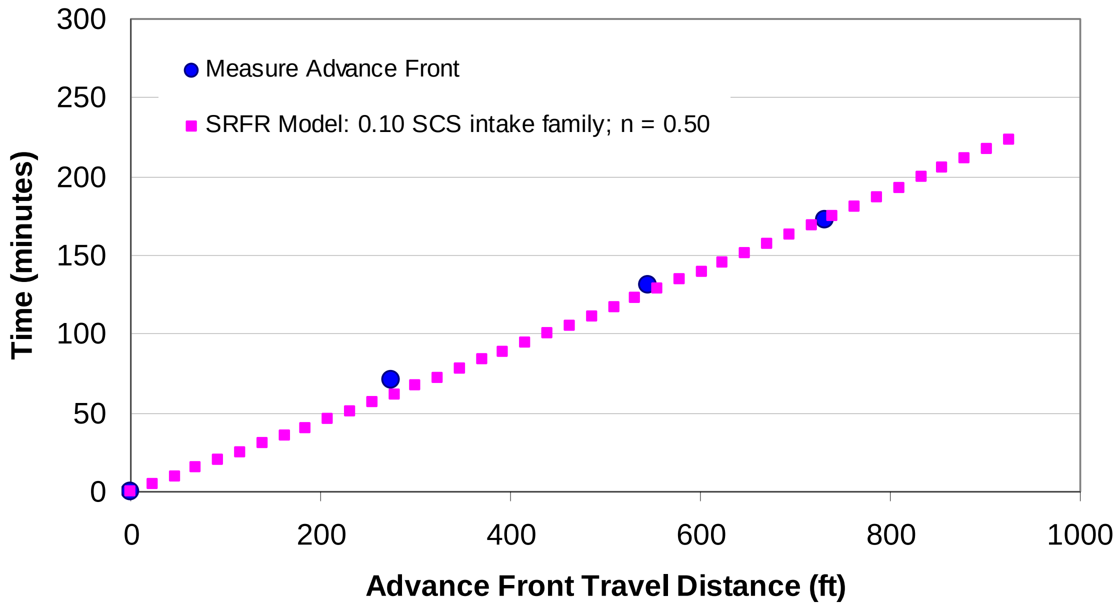


Figure 2. Correlation of field flood irrigation test results to calibrated SRFR model advance rate estimates.

Furthermore, the new irrigation delivery system was designed such that operational adjustments could easily be accomplished during commissioning to refine the irrigation water management plan. Because the advance fronts were not rectangular as assumed in SRFR, linear advance front travel distances were calculated by dividing the total wetted areas at each mapped time interval by an average inflow width after about 1 hour of flow when the source area had stabilized.

WATER CONSERVATION

In order to evaluate the potential water conservation benefits of this project, water balances were projected for pre- and post-project irrigation water management. Since the pre-project system did not have a flow meter, historic irrigation operations were reconstructed from an irrigator survey. However, the historic operations were very simple with two 12-hour sets per day for 24-hour-per-day operations over a 173-day irrigation season. Consequently, gross irrigation deliveries and total groundwater pumping could be reasonably estimated from this information. Post-project deliveries were based upon the design irrigation water management plan, and water budget distributions were based upon SRFR model results.

Pre-project operations of this wild flood irrigation system were dictated primarily by labor limitations and the lack of any automatic water control strategy or scheduling to match deliveries with crop needs. The even application of water throughout the irrigation season thus resulted in very low application efficiency in the spring and fall and increased efficiency levels in the peak summer months. Estimated application efficiencies ranged from 20 percent in May to 42 percent in July with an annual average of about 28 percent. On average, approximately 41 percent of applied water was estimated to run off as tailwater and 31 percent was estimated to be returned to groundwater as deep percolation.

The most significant improvement of the new water conservation measures for this site will be realized in following the defined irrigation water management plan, and, with a pump timer, having the ability to run shorter irrigation sets. For post-project operations, the landowner was reticent to commit to any greater than two irrigation sets per day as is currently practiced. Consequently, a rotation was developed such that the field could be irrigated with the same two visits to the field each day. During the peak summer months, 7.5-hour sets on an 8-day rotation will replace the 12-hour sets on a 20-day rotation. This will also translate into 15-hour-per-day operations as opposed to 24-hour-per-day irrigation. By lengthening the return interval for irrigations during the lower demand portions of the irrigation season, further savings will be realized. With the revised field layout and management, an application efficiency of approximately 57 percent is projected with 38 percent lost to tailwater runoff and an estimated 5 percent lost to deep percolation.

As shown in Figure 3, the water conservation measures implemented on this project are anticipated to significantly reduce total groundwater pumping, deep percolation return flow to groundwater, and tailwater return flows to surface water while maintaining approximately the same total consumptive use. Although the fraction of tailwater generation during an individual irrigation event is only expected to decrease a few percent, the total reduction in gross irrigation deliveries will substantially reduce the volume of surface water return flows over an irrigation season. The increased total application efficiency will be realized primarily in the reduction of excess infiltration and deep percolation losses. Due to the fine-textured soils at this site, head ditch seepage losses are estimated to be fairly minor in the range of 5 ac-ft per year or about 2 percent of the annual net irrigation requirements.

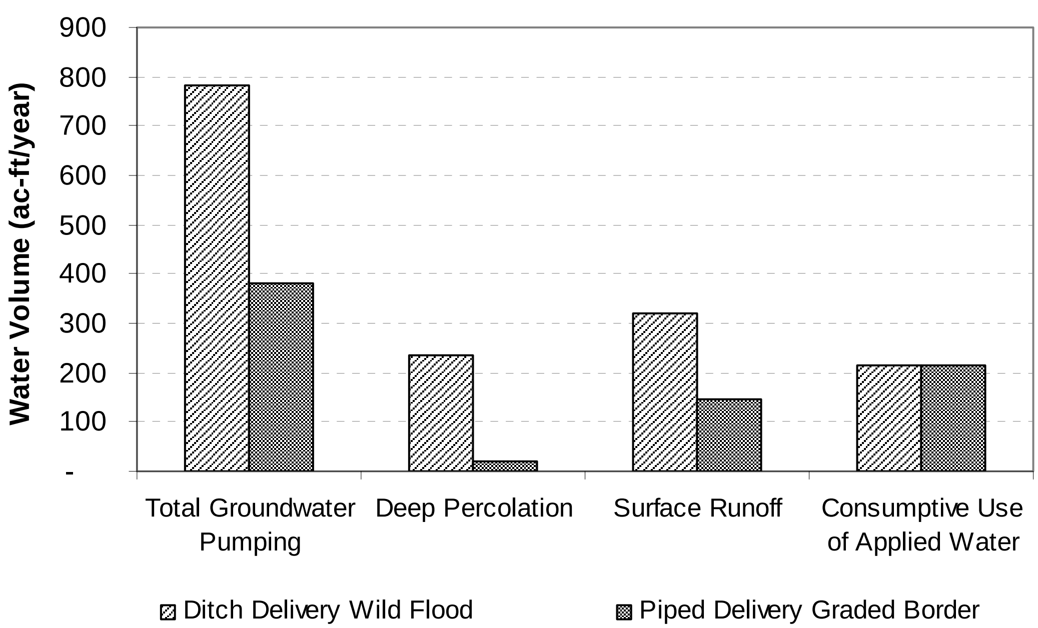


Figure 3. Estimated water balances for pre- and post-project irrigation management.

Long-term monitoring of groundwater wells on and around this project site have shown that groundwater levels have declined more than 40 feet over the last 50 years. Projecting the water conservation impacts of this project across the subbasin at almost 400 ac-ft/year of reduced pumping for every 100 irrigated acres could result in a significant positive impact to this aquifer system as an additional benefit.

ECONOMICS OF ENERGY CONSERVATION

With the scheduled phase out of preferred energy rates for agricultural use in the Upper Klamath Basin, irrigators are facing energy bills that will increase over 10 times from 0.6¢/kW-hr to approximately 5.7¢/kW-hr over a 6 to 7 year transition period that started in 2006 (Jaeger, 2004 and personal communication with Pacific Power, April 2007). Consequently, conversion of irrigation delivery methods from gravity systems to pressurized systems must be undertaken only with a complete understanding of the long-term operations cost implications. By implementing on-farm irrigation efficiency enhancements that reduce the total pumping energy demand without any increase in labor requirements, the capital cost of system improvements can be recouped within a reasonably short period of time and will reduce total operations costs in the long-term.

At fixed power rates that irrigators have enjoyed over the past 50 years, there has been little economic incentive to increase irrigation efficiency at the farm scale. Using the irrigation efficiency enhancements of this project as an example, the capital investment in system improvements at approximately $745 per acre would take 98 years to pay off at a 5 percent discount rate or 25 years accounting for a 75 percent cost-share incentive provided through the EQIP (Table 1). Such investments would hardly make economic sense when evaluated upon annual operating costs alone. However, this balance will change dramatically with the increased energy rates such that this project would have a 10 year payback period using the same assumptions and could be further reduced to less than a 3 year period with the EQIP incentive payments.

The additional economic incentives for energy conservation may become a vehicle for encouraging water conservation in the basin. However, most flood to sprinkler conversion projects will increase energy demands over pre-project usage and will not benefit from this economic incentive. A pumping cost comparison between wild flood, graded border, and sprinkler irrigation is presented in Table 2 and takes into consideration the differences in gross irrigation requirements and pumping power requirements for each alternative. Because of the additional pumping lift required for pressurized systems, water costs for this project would be increased from approximately $18/ac-ft to $38/ac-ft. Even though gross irrigation requirements are lower for the higher efficiency sprinkler irrigation (75% assumed efficiency), the increased unit pumping costs would cause the total annual pumping cost for sprinkler irrigation on this project to be approximately $4,200 per year greater than for graded border over the 100 acres.

Irrigators facing a ten times increase in current energy bills over the next six years will have to weigh irrigation system upgrade decisions carefully. This will be especially important for those who are irrigating low margin pasture where the capital investment in water conservation measures will be hardest to recover.

Table 1. Economics of energy conservation for 100-acre flood conversion project

Item	Value
Capital Expenditure for System Improvements	$74,500
EQIP Cost Share Funding	$55,875
Net Capital Expenditure	$10,995
Discount Rate	5%
Pre-project Annual Energy Cost at 5.696¢/kW-hr	$13,949
Annual Energy Cost Savings at 5.696¢/kW-hr	$7,188
Payback Period w/o Cost Share at 5.696¢/kW-hr	10 years
Payback Period w/ Cost Share at 5.696¢/kW-hr	3 years
Pre-project Annual Energy Cost at 0.6¢/kW-hr	$1,469
Annual Energy Cost Savings at 0.6¢/kW-hr	$804
Payback Period w/o Cost Share at 0.6¢/kW-hr	98 years
Payback Period w/ Cost Share at 0.6¢/kW-hr	25 years

Table 2. Pumping cost comparison between irrigation methods for 100-ac project

	Wild Flood Irrigation	Graded Border Irrigation	Sprinkler Irrigation
Application Efficiency	28%	57%	75%
Annual Gross Irrigation (ac-ft)	784	380	289
Unit Pumping Cost ($/ac-ft) [a]	$17.80	$17.80	$38.03 [b]
Annual Pumping Cost	$13,949	$6,761	$10,978

[a] Pumping cost projected at 5.696¢/kW-hr

[b] Additional 50-hp of pumping power required for sprinkler irrigation in excess of 44-hp required for flood irrigation

OPPORTUNITIES FOR INCREASED BENEFITS

While benefits can be attained on a field by field basis, far greater opportunities exist as the scale of the area involved is increased. Most wild flood pasture systems are operated in units ranging in size from 10 acres to 100 acres. However, tailwater generated on each field is often routed through down-gradient fields where it can be recaptured and reused. Wherever possible, improvements should be planned and implemented over a scale sufficient to encompass a complete hydrologic unit from the initial irrigation water source to the final discharge of any unused tailwater to main conveyance channels or surface water.

CONCLUSIONS

The water and energy conservation impacts of this project case study provide a good example of the potential benefits that can be realized by implementing flood irrigation efficiency enhancements. With relatively simple engineered enhancements to wild flood application systems, significant reductions can be realized in groundwater pumping, tailwater return flows to surface water, and energy consumption with minimal impacts to operations labor. While the EQIP support for these projects is targeted towards alleviating water supply and water quality stresses, a smart irrigator can take advantage of this program for the additional tangible benefits of energy conservation and reduced pumping bills. For example, the cost-share reimbursement provided through this project can reduce the period of return on capital investments from 10 years to 3 years. While irrigated pastures represent a significant demand on water resources in the basin, the marginal economics of these systems may be better suited to enhancing the efficiency of surface irrigation systems rather than conversion to sprinkler systems that are more costly to install and to operate.

REFERENCES

Clemmens, A.J., D.E. Eisenhauer, and B.L. Maheshwari. 2001. Infiltration and Roughness Equations for Surface Irrigation: How Form Influences Estimation. Proceedings Paper from 2001 ASAE International Meeting, Sacramento, CA, July 30-August 1, 2001.

Jaeger, W.K. 2004. Energy Pricing and Irrigated Agriculture in the Upper Klamath Basin. Oregon State University Extension Miscellaneous 8846-E, July 2004.

Strelkoff, T.S., A.J. Clemmens, and B.V. Schmidt. 1998. SRFR v. 3.31. Computer Program for Simulation Flow in Surface Irrigation: Furrows-Basins-Borders. USDA-ARS U.S. Water Conservation Laboratory, Phoenix, AZ.

USDA-NRCS. 2004. Upper Klamath Basin: Opportunities for Conserving and Sustaining Natural Resources on Private Lands. USDA Natural Resources Conservation Service, September, 2004.

A METHOD DESCRIBING PRECISE WATER APPLICATION INTENSITY UNDER A CPIS FROM A LIMITED NUMBER OF MEASUREMENTS

B.Molle[1]
J.Granier[2]
A.Drechsel[3]

ABSTRACT

Centre pivot irrigation systems are known for their irrigation distribution performance potential. Unfortunately the performance analysis of centre pivot irrigation systems is often restricted to the uniformity of distribution. Depending on the characteristics of the applied rainfall, a system designed for high uniformity does not guarantee a high application efficiency once the system is in operation.

A method is proposed in the present paper to analyse the average rainfall depth of application and kinetic energy delivered to the soil by individual droplets all over the machine.

The method requires water distribution profiles, the distribution of droplet size and velocity along the radius of coverage for any nozzle, and pressure and height of the emitter installed on the machine. Considering the number of nozzles and the range of pressure applied, there is the need for a method calculating: the emitter maximum radius of coverage, then the rainfall distribution profile, then the droplet distribution and finally the associated kinetic energy delivery. These parameters are calculated on a new model of classical design sprayers proposed by IWT Company.

These results are being integrated on a centre pivot nozzle chart design software presented in the poster session.

INTRODUCTION

Irrigation equipment manufacturers commonly emphasize the uniformity of application to describe their systems' performance. Uniformity describes the proportion of area over/under irrigated with regard to the average application. The efficiency of the application is for the most part not considered. Efficiency is assumed here, as the ratio between the applied water that is useful to the plant and the total water applied to the plot. In this case we do not account here for the specific needs of soil leaching for example.

In general, farmers tend to apply more water than necessary to account for the various sources of system inefficiencies. The objective is to assure a minimum application depth in the least sprayed areas. As a consequence the productivity of the water obtained (in kg m^{-3}) by the agricultural systems is generally lower than the potential.

[1] Research Engineers, G-EAU Cemagref, Manager of LERMI, bruno.molle@cemagref.fr
[2] Doctor Engineer, G-EAU Cemagref, LERMI, Jacques.granier@cemagref.fr
[3] Director of IWT company, arno.drechsel@iwtirrigation.com

Factors that affect the uniformity of application and, therefore, system efficiency include:

- Rainfall rate exceeding the surface storage capacity and the soil's infiltration rate. Such problems are frequently observed under centre pivot distal end and usually increase as the irrigation season progresses;
- Modification of the soil's surface by the impacting water droplets , which can gradually cause soil surface sealing and increased runoff;
- The drift of small drops under the influence of the wind.

Detrimental effects of irrigation inefficiency and non-uniformity increase when fertigation or chemigation are practised.

The designers of centre pivots tend to dimension their distribution capacity to avoid any risk of local water deficit. A moderate excess of water is generally well accepted compared to default which rapidly generates visible crop reactions and associated yield reductions.
In the case of centre pivots, the continuous variation of the water application rate along the boom makes their control more complicated than on fixed installations.

Consequently to improve centre pivots application efficiency, we have to adapt the water application characteristics to soil intake capacity, to climate conditions and to the possible sensibility of plants or the seed beds. To answer this concern we have to know:

- the amount of applied water per unit time or average irrigation intensity, compared to soil infiltration increased by surface storage capacity, at different points along the path of the machine;
- the number, size and velocity of droplets over the wetted area;
- the sensitivity to wind drift and evaporation, according to droplet size distribution, specially the proportion of drops smaller than a given limit.

To anticipate any control of all the parameters of application, it is necessary to know precisely their distribution at any point under the machine according to the combination of nozzle and pressure. A first approach has been presented by Molle (2002) on centre pivot impact sprinklers. The present application undertakes the same principles and adapts them to KSN® sprays manufactured by IWT. Such an approach allows for the selection of optimum design parameters taking into account both soil infiltration and wind drift risks.

MATERIAL AND METHODS

We have been working with the centre pivot sprayer KSN® (.1) manufactured by IWT in Austria. Its body(a) can accommodate 43 different nozzle(b) diameters, ranging from 1.8mm to 10.3mm (numbered 9 to 52), and 5 different deflectors(c).

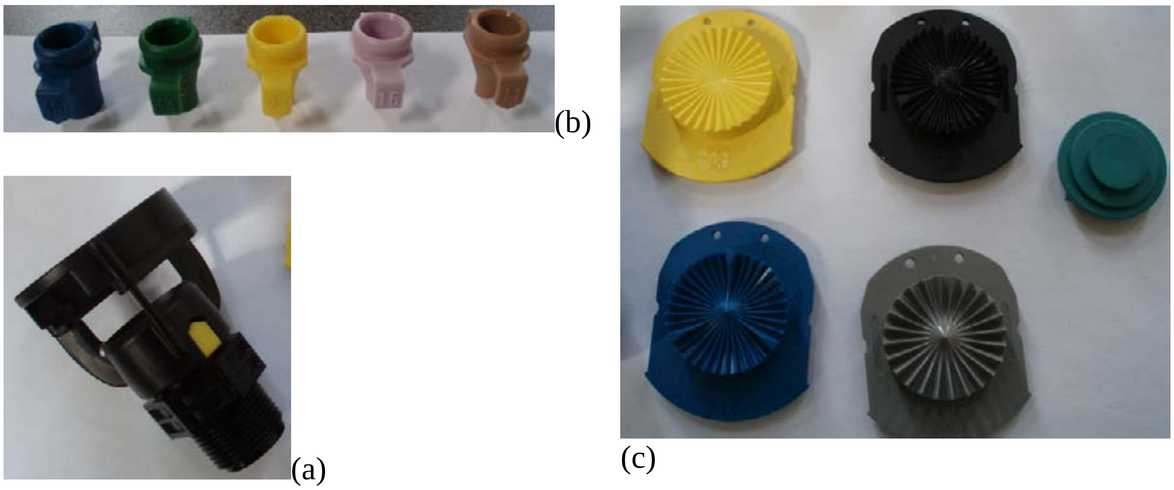

(b) (a) (c)

Figure 1. KSN® Spray

This spray is connected to a hose pipe that positions the head at 1 to 3m from the ground or crop;, the range of operating pressure is 20 in 200kPa.

Considering the wide range of possible nozzle/pressure/height combinations it is not economically feasible to measure all the combinations. Thus we have tried to describe mathematically the distribution curves of every combination, from a limited number of measures, from which others (none measured) have been interpolated. We have been working on:

- the blue deflection plate, dividing the main jet issuing the nozzle in 33 sub-jets, emitted at 7° from the horizontal, the 4 other deflection plates are currently under evaluation;
- using 5 nozzles (11, 16, 23, 34, 49);
- at 5 pressures: 40, 80, 120, 160 and 200kPa, 3 only for some combinations to analyse the effect of height. This allows to cover a range of 90 to 5400l/h (when the whole series covers 60 to 6150l/h);
- the height between nozzle and measurement points was 1m, and for some limited combinations 2 and 3m;

Three types of measurements were conducted in the laboratory: flowrate versus pressure curve, radial water distribution curve and droplet size and velocity distribution according to the distance from the emitter.

Evaluation of the flowrate versus pressure curve

Nozzle evaluations were conducted using the ISO-9261 standard; 5 samples of 5 diameters of nozzles were selected and evaluated under 5 pressures (40, 80, 120, 160 and 200kPa), successively at increasing then decreasing pressure. The test facility allows regulating pressure with a precision of ±2kPa and measuring flowrate at ±5l/hour. The pressure is measured as closely as possible from the nozzle (Figure 2), this measurement doesn't account for the deflection plate used. For each nozzle diameter we have selected the average nozzle, the characteristics of which are the closest to the average of the 5 samples of the same diameter. This nozzle is then used for all the following investigations.

Evaluation of the radial water distribution curve

The radial distribution curve was established according to a protocol derived from the ISO-15886 (2005) standard. Collectors are positioned every 30cm on the first metre, then every 15cm on the rest of the radius. Collectors are 25cm in diameter with sharp edges, 25cm in height, and white in colour. Their mass is individually weighed on a scale after every test with a precision of ±0.1g (Figure 3). Every rainfall measurement is repeated 2 to 3 times according to the distance. To obtain an average water distribution curve, the spray is attached to a vertical pipe rotated by an electric engine at a speed of 2 rph. It is placed in a surrounding case preventing projections in the measurement area. Duration of the tests was 60, 90 or 120minutes. A distribution curve was obtained by averaging from 2 to 4 spray rotations.

After each rainfall measurement, a reconstituted flow is calculated from individual measurement integrated over the surface area represented. To be validated, a test shall show a reconstitution ratio between 95 and 105%.

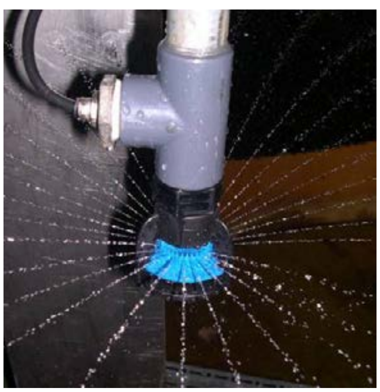


Figure 2. assembly of the Spray KSN used for the tests

Figure 3. measurement facility for average rainfall distribution tests ➔

The radial distribution of rainfall of each of 5 nozzles was measured for a height of 1m and for a pressure of 40, 80, 120, 160 and 200kPa. Nozzles 16 and 34 were also evaluated at 2 and 3m height for a pressure of 120kPa, the nozzle 23 was also evaluated at 80 and 160kPa for the same heights.

The objective is to investigate a general expression representing the rainfall distribution measured for each couple Nozzle-deflector. We have first calculated for every curve the value of the maximum radius R. According to the ISO-15886 standard, it corresponds to the point at which the rainfall collected is 0.3mm/h. This value can be interpolated linearly from the furthest two rainfall measurements recorded for every combination.

The measured values were standardized to make them comparable among each other. In this purpose every rainfall measured is converted in volume (rainfall multiplied by the surface element represented proportional to the distance from sprinkler head) divided by the total volume measured by the flow meter. The standard volumes are represented against the standard radius (r/R). This allows obtaining series of comparable curves, from which we can generalize the representation of the distribution according to every parameter of dimension and operation.

Evaluation of the droplets size and velocity distributions

This measurement is established at 7 points: 30, 40, 50, 60, 70, 80 and 90 % of the maximum radius, using a DBS (Dual Beam Spectrometer) designed by Cetp (www.cetp.fr), which is described by Delahaye and al. (2006) and marketed by Cimel-electronics (www.cimel.fr).
The DBS is constituted by two parallel IR beams of 2mm of thickness, separated by a distance of 2mm, the width is 40mm and the length 250mm. These beams are received by two photodiodes generating a tension varying according to the intensity of the light. When a particle crosses the beams, the tension decreases proportionally to the size of the particle (Figure 4). The time gap between both signals is inversely proportional to the velocity of the particle. Every particle identified is described by a date of passage, a size and a velocity. A fourth parameter indicates the quality of the detection. To limit the measurement error on the velocity, the beams are positioned perpendicular to the average trajectory of particles. To avoid any risk of projections of droplet impacting sensor's frame, the sensor is wrapped with an absorbing cover (Figure 5).

A particle of water in flight presents an elliptic section under the influence of air friction. The size of every particle is calculated from its shadow, as identified by the receiving diode, converted in equivalent diameter by using the algorithm of Pruppacher and Pitter (1971). This correction is active only for particles bigger than 1mm.

Each measurement is constituted of a minimum of 5000 particles with a range of equivalent diameter from 0.1 to 10mm.

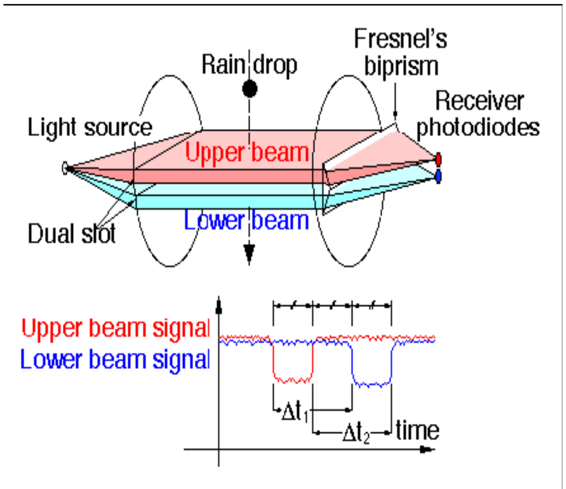


Figure 4.Operating scheme of the DBS (source Cetp)

Figure 5. DBS in measurement position, perpendicular to average droplets path, wrapped with anti-projection coating

The DBS is regularly calibrated by using calibrated steel balls crossing the beams with increasing falling velocities (ellipticity correction is neutralised). The average error varies according to the equivalent diameter of particles, between 5% for the particles less than 500µm, and 2% for particles up to 5mm of equivalent diameter. A calibration made by means of drops calibrated by needles of syringe, falling from 4m height, weighted by a precision scale compared to equivalent volume calculated from the sensor gave an error of 3% for droplets between 2.0 and 3.5mm.

This error is higher than observed with calibrated balls for two main reasons: the variability of the shape of particles, a falling velocity lower than the maximum value which is considered in the correction of Pruppacher and Pitter (1971).

For every measure we calculate the following parameters:

- Collected volume (converted in mm) and measured rainfall (mm/h): sum of volumes of the sampled droplets reported over the sampling surface area of the sensor and to the time of measurement;
- Sauter Diameter

$$D_{32} = \sum n_i d_i^3 \Big/ \sum n_i d_i^2$$

is the ratio between the cumulative droplet volumes (d_i^3)and the cumulative droplet surface (d_i^2). It gives, on the average, an indication on droplet drag, thus of their sensitivity to wind and their potential evaporation surface;

- The scatter of the distribution is evaluated by *DispN10* and *DispN25* for the distribution by numbers and *DispV10* and *DispV25* for the distributions of volumes, with:

$$DispN10 = \left(D_{N90} - D_{N10}\right)/D_{N50}\ ,\ DispN25 = \left(D_{N75} - D_{N25}\right)/D_{N50}\ ,$$

  where D_{Nxx} is the diameter at which xx% of the number (respectively volume) is under the given limit of diameter. This parameter gives no idea of the possible asymmetry of the distribution. It doesn't make any problem for this sprayer distribution. It may not be correct for impact sprinklers for which the dispersion of droplet diameters is generally asymmetrical;
- The water application intensity, in mm/h, inside a sliding window of 60, 30, 20, 10, 5, 2 and 1seconde. This parameter helps understanding the chronology of water application and its heterogeneity during watering time. This parameter is more adapted to single jet distribution than spray type one;
- Different way of calculating kinetic energy (KE) can be used for sprinklers benchmarking:
  - total KE related to application duration (Wh),
  - averaged according to a unit surface area (W/m²) during a given time interval (60, 30, 20, 10, 5, 2, 1second),
  - integrated over the whole radius (J/kg).

RESULTS AND DISCUSSIONS

Evaluation of the flowrate versus pressure distribution curve

The measurements were conducted with increasing and decreasing pressure. This showed that there was no hysteretic effect on these nozzles, in the interval of pressures considered. For each of the 5 evaluated nozzles we tried to adjust a curve using an equation such as:

$$Q = \alpha \times P^{x}$$

With Q: flowrate and P: pressure measured at sprayer inlet. Results of adjustment are given in the Table 1, considering all the measurements of 5 nozzles, for each diameter.

Table 1: adjusted parameters for Q=f(P)

Nozzle	Size 11	Size 16	Size 23	Size 34	Size 49
Coefficient α	0.1702	0.403	0.8234	1.7706	3.6346
Exponent x	0.5015	0.5146	0.5179	0.521	0.519
Global R2	0.9974	0.9994	0.9987	0.9999	0.9996

This analysis using the nozzle diameter allows describing exactly the equation of every nozzle. For calculating the water distribution of a centre pivot, a general expression of flowrate delivery at each outlet is necessary. The general expression taking into account the diameter of nozzles, adjusted by the least square method, is:

$$Q = 0.040 \times D^{1.984} \times P^{0.517}$$

With a determination coefficient R2=0.998. A comparison of the values measured on the 5 diameters of nozzles and the values calculated by the model is given in Figure 6.

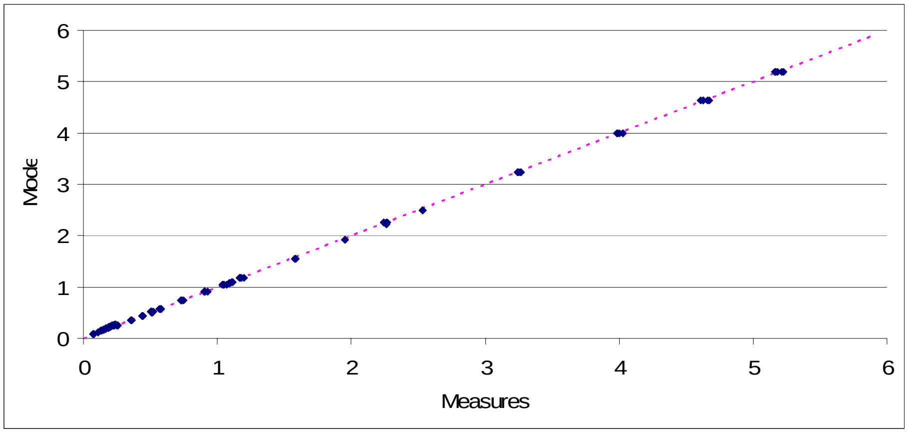


Figure 6. Comparison between measured and calculated flowrates for the 5 nozzles diameters analysed

The average error is $10^{-4} m^3/h$, and the standard deviation of the error of $2.2\ 10^{-2} m^3/h$. This error is bigger on the smallest diameters.

Evaluation of the radial water distribution curve

Figure 7 shows a sample of measurements results obtained on 9 of 33 evaluated combinations, for the 23 (4.6mm) nozzle.

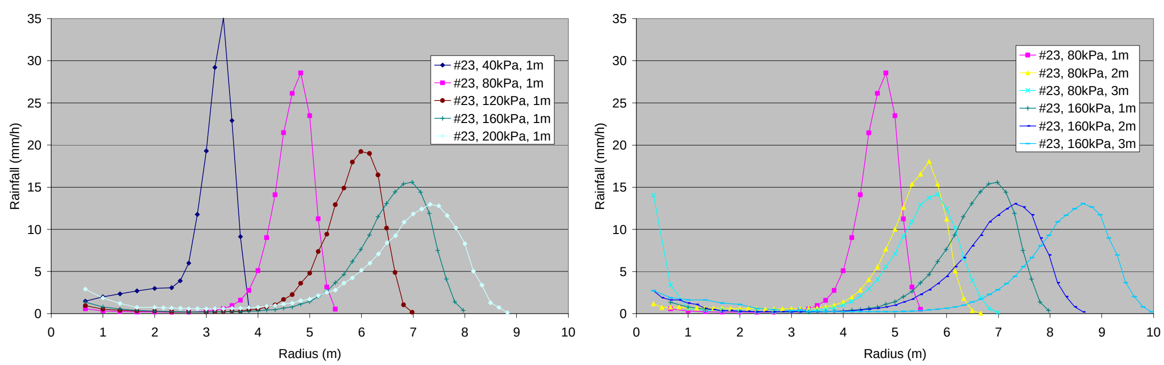


Figure 7. Nozzle 23, Effect of pressure and height on rainfall distribution

To give a general representation of the distribution curves, it is necessary to standardize data according to the radius. We calculated the maximum radius for every combination, then fitted these radii to the operating and dimension parameters of the spray. We first used the equation proposed by Kincaid (1982) for impact sprinklers: $R = \alpha\left(Q \times \sqrt{P}\right)^{\beta}$, but results were unsatisfactory. After several attempts, we selected a power function undertaking all the parameters considered for a given deflector:

$$R = a \times D^b \times P^c \times Q^d \times H^e$$

With R: radius in m, D: nozzle diameter, P: pressure in bar, Q flowrate in m^3/h and H: height above collection surface in m.

The parameters calibrated for the blue deflector are: a=43.4; b=-1.215, c=0.109; d=0.832; e=0.24 and the coefficient of determination is $R^2=0.97$.

The values measured and adjusted are shown in Figure 8:

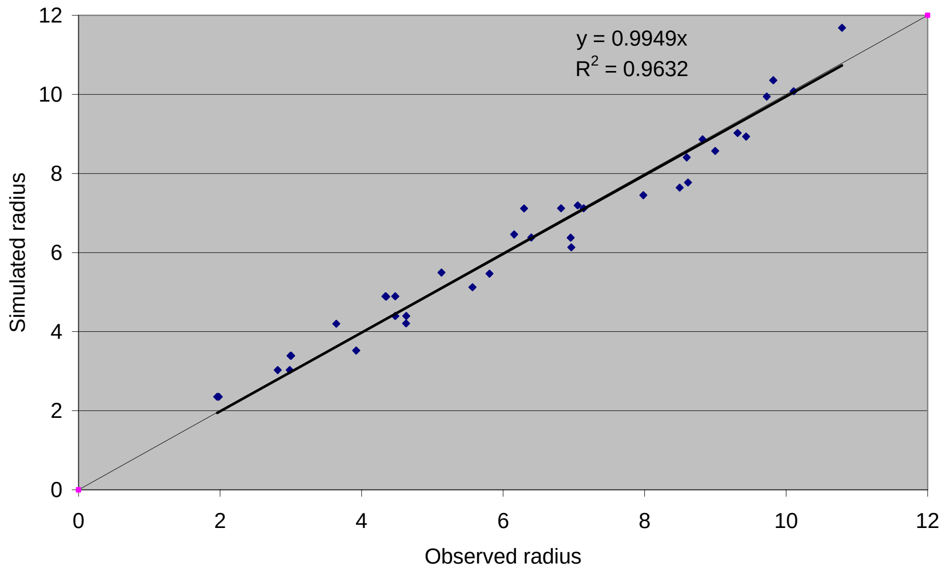


Figure 8. Comparison of measured and calculated radius

The average error calculated is: 0.014m with a standard deviation of 0.47m, the interval of variation of the error is [-0.89m ; 0.85m], corresponding to a relative deviation varying from 2% to 20%. We consider this result satisfying for our objective of calculation of the rainfall distribution curve of a centre pivot.

This type of adjustment tested on the other deflectors gave similar results. We still have to refine the proposed model which undertakes redundant parameters: the flowrate Q on one hand, the diameter D and the pressure P on the other hand.

The standardised water distribution was unsatisfactorily simulated using the standard radius, and normal distribution functions (Figure 9). As an alternative, we calculated 10 characteristic values for every distribution, the first one at 5% of the radius and the rest at increments of 10 % of the radius. From these values, the water distribution of unevaluated nozzle-pressure combinations will be calculated using interpolation.

An attempt is to be made in the future with a probabilistic method proposed by Legat, Molle (2000).

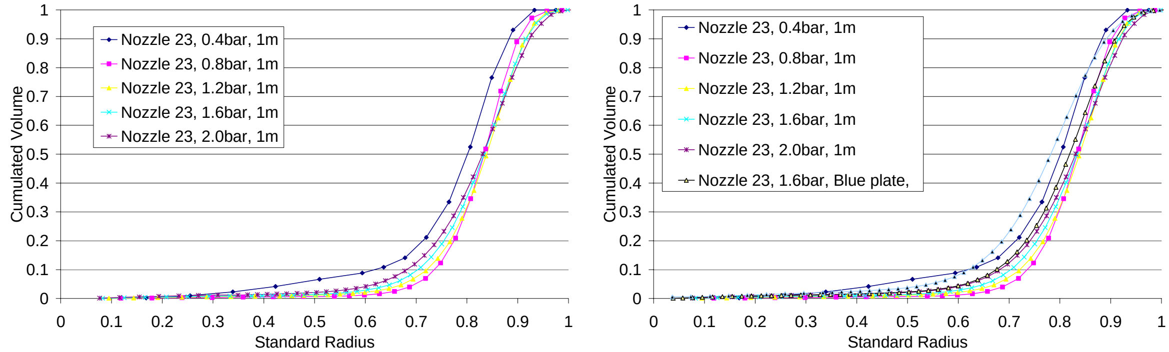
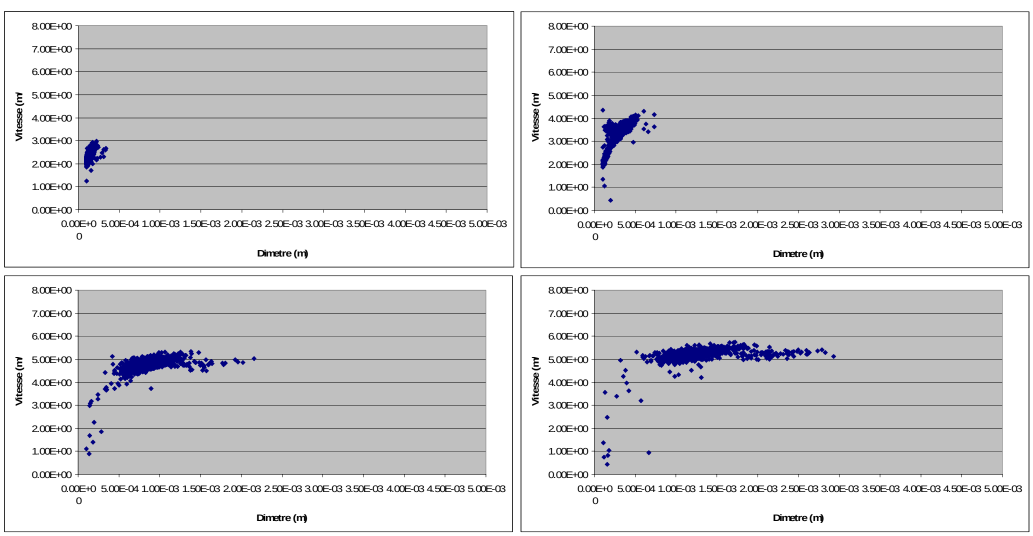


Figure 9. Example of standardised water distribution for nozzle 23 according to pressure and height

Evaluation of the droplets distribution sizes

Figure 10 shows the results of droplet sampling at 5 radial points. Note that particle sizes are growing with distance from the sprayer. This size varies from 0.1mm (limit of DBS detection) to 3mm. At the lower pressures the maximum size can exceed 5mm. The dispersion of the jet in particles is rather rapid on this type of spray, and droplets distribution parameters are varying more rapidly than what is observed with sprinkler jet type distributions. Big particles having a lower drag coefficient travel further than small ones, their velocity at impact on the soil is 6m/s on the average.



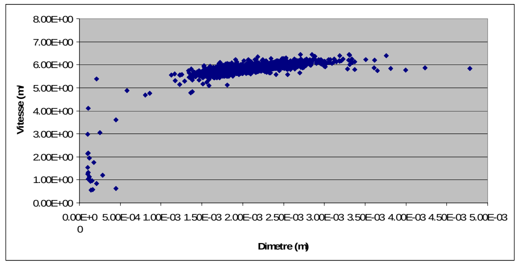


Figure 10. Nozzle 23, pressure 160kPa, height 1m, Radius : 2.66m (33%), 4.00m (50%), 5.66m (71%), 6.33m (79%), and 7.00m (88%)

The analysis of these distributions (Figure 11) shows that they are generally unimodal, except in several combinations at the far end of the radius, where some big particles eventually burst into smaller particles, as observed in the last chart of Figure 10. We can also note that distribution curves in volume are shifted to the right, with regard to distribution in numbers. In our example, beyond 4.3m (75 % of the radius), 80% of the volume of water is applied in the form of droplets bigger than 1mm. On a spray with rotor, for example we have observed a similar phenomenon but with droplets bigger that 2.5mm. The predominance of droplets bigger than 2mm decreases the sensitivity of water distribution to the wind (Hendawi and al. 2005) but increases considerably the risks of excess application intensity.

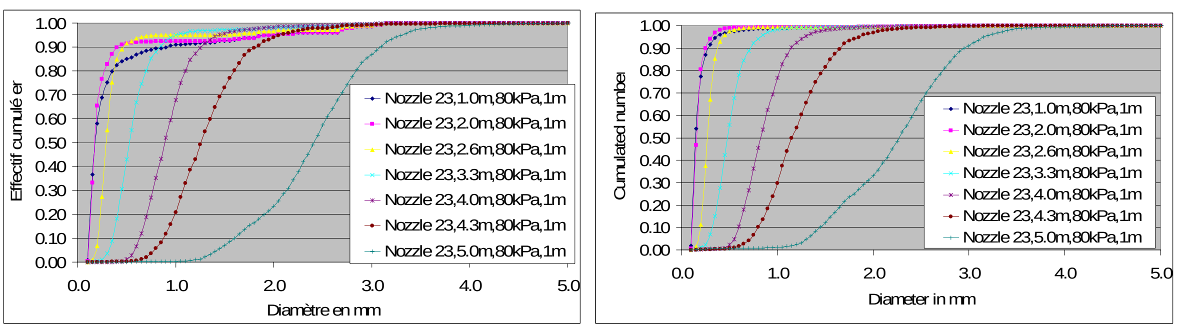


Figure 11. Cumulated Numbers and Volume per class of droplets diameters for nozzle 23 at 80kPa

To qualify the distribution of droplets diameters D_i regarding their size, the best indicator is the Sauter diameter: $D_{32} = \sum D_i^3 / \sum D_i^2$. The use of NMD or D_{N50}, and VMD or D_{V50} (Number Median Diameter, and Volume Median Diameter), simpler to calculate could also be used.

We noticed that for every nozzle diameter the distribution of D_{32}, follows a quadratic law according to standard radius as illustrated in Figure 12. The same observation is made for others nozzles. We thus tried to calibrate a general equation adjusting all the values of D_{32}, related to the standard radius, whatever is the distance from the sprinkler.
All the data measured was fitted with the equation:

$$D_{32} = a \times \Phi^b \times P^c \times R_{\%}^d ;$$

With Φ : number of nozzle diameter, P: pressure in bar, R: standard radius in %. The parameters are: a=0.168, b=0.92, c=-0.163, d=2.781, the coefficient of determination is R^2=0.93. The correlation between measured and calculated values is given in Figure 13. It is considered correct according to the accuracy required for centre pivot distribution simulation.

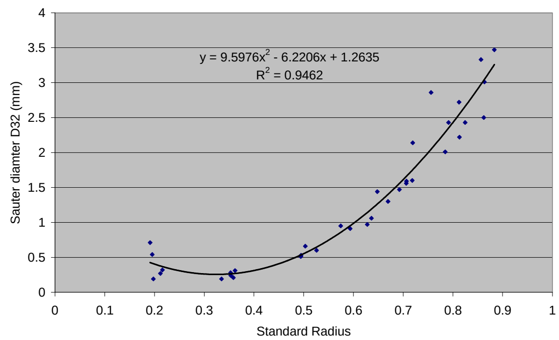


Figure 12. Sauter Diameter (D_{32}) for nozzle 34 between 40 and 200kPa, et 1m height

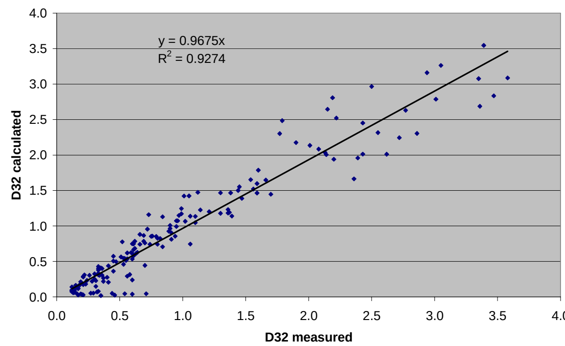


Figure 13. Correlation between Sauter diameters (D_{32}) measured and simulated for KSN spray equipped with the blue deflector, a nozzle diameter from 11 to 49, a pressure from 40 to 200kPa, and 1m height

If we observe the scattering of the distributions in Figure 14, we can notice that *DispN10* and *DispN25* don't show any trend in variation. They could be considered as constant with respective means of 0.72mm and 0.36mm. On the other hand, the values *DispV10* and *DispV25* tend to decrease with the standard radius. The presence of several big particles (not appearing in scattering in number) in the beginning of radius, can be due to rebounds or to local perturbation of the distribution by the supports attaching the deflector to the body of the sprayer.

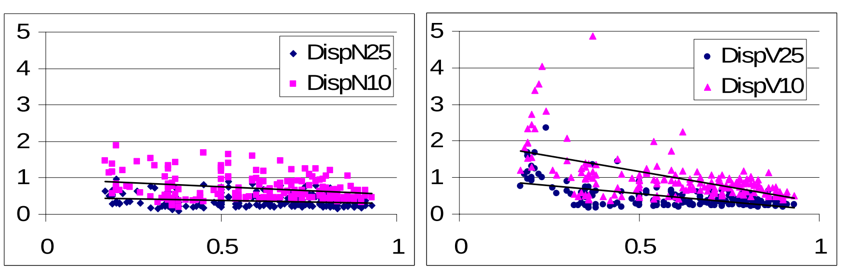


Figure 14. dispersion values of numbers and volumes for KSN spray equipped with the blue deflector, the 5 nozzles diameters from 11 to 49, 5 pressures from 40 to 200kPa, and 1m height

Evaluation of the water application intensity

The analysis of water application intensity during a limited sliding time interval shows an increase of intensity when time interval decreases. It reaches regularly and overtakes 100mm/h, for the pressures of 80 to 200kPa, with higher values up to 400mm/h for the pressure of 40kPa. The differences between the values in 60, 30 and 20secondes and the mean value are small.

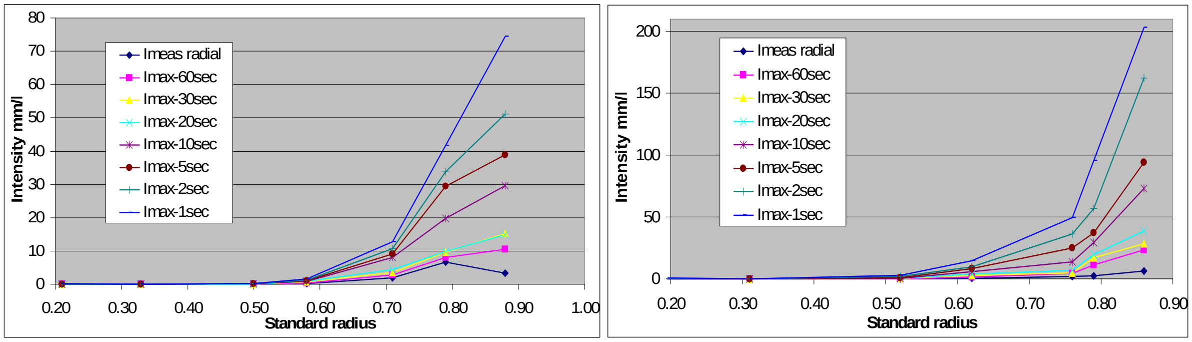


Figure 15. Nozzle 23 and nozzle 49, 160kPa, 1m, variation of maximum water application intensity related to reference time

For the biggest nozzle, which tends to saturate the deflector, these values overtake a 150mm/h for an interval smaller than 5seconds whatever is the pressure. Such intensities, even if they last shortly, can generate rearrangements of soil surface particles and initiate local saturation and runoff phenomena often observed in centre pivots distal end. Nevertheless the detrimental effect of such intensities will rely on particle number and size, not accounted in intensity analysis. That is the reason why the analysis of intensity alone is not enough, if no information is given on the kinetic energy of droplets when impacting the soil surface.

Evaluation of the Kinetic Energy (KE) distribution according to time (Wh)

As for the water application intensity approach, we tried to identify the homogeneity of the application according to time. Thus we have calculated the values of Ec (Wh/m ^{2}) during a sliding time interval of 60, 30, 20, 10, 5, 2 and 1 second. We can note that the values calculated for a window of 20 to 60secondes are equivalent. It is the same for a window of 1 to 5secondes (Figure 16). It means that the minimum time scale of KE observation for this spray must be close to 5secondes. In other words, during the passage of a jet issuing the spray, we can consider that the maximum intensity periods last less than 5secondes. This period is far over of what is observed under sprinkler jets, where maximum intensity period are concentrated on shorter period (less than 2 seconds) with higher resulting KE.

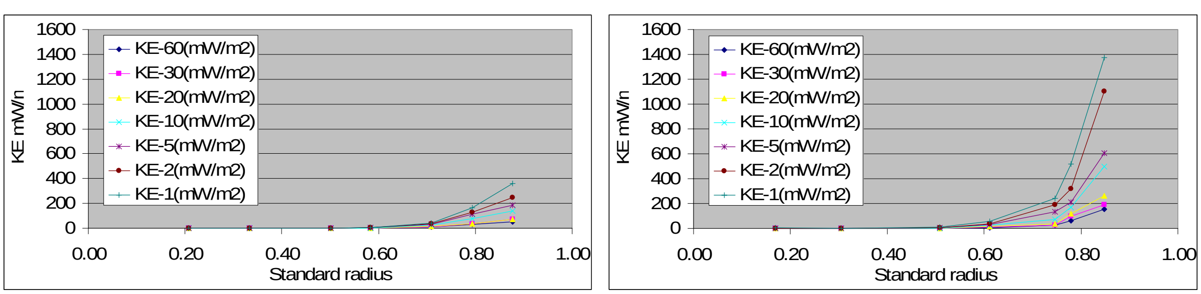


Figure 16. Nozzle 23 and nozzle 49, 160kPa, 1m, variation of Kinetic Energy of water application related to reference time

More generally Figure 17 shows that the maximum KE tends to decrease when the pressure increases between 40 and 80kPa for all the nozzles, then it remains more or less constant for the other pressures. In absolute value the pick KE increases strongly with nozzle diameter.

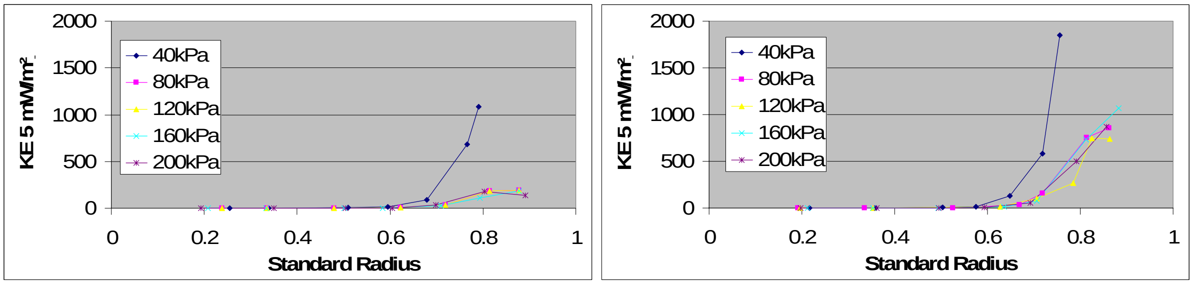


Figure 17. Nozzle 23 and nozzle 34, effect of pressure on maximum KE observed during a 5 second period

From these first results we can draw some conclusions:

- The effect of the high flowrate is less important on droplets KE when reaching the soil than the effect of pressure. These pressures should be avoided while the crop is not covering the soil, in case of fragile soils or seed beds;
- The KE of the water distribution is concentrated on approximately 30% of the radius (60 to 90%), below 70% of the radius the contribution is coming from very small particles which leave progressively the main jet or which result from the explosion of bigger particles;
- Beyond 90 % of the radius the number of particles obtained is so reduced that it is complicated to conclude.

Evaluation of the Kinetic Energy (KE) distribution in J/kg according to radius

The previous analysis shows us how KE is varying when a unit time interval is considered, but we lack the understanding of total KE delivered, disregarding the time duration of application, but according to the volume of water applied. This kind of parameter makes it possible to compare the different types of emitters between each others.
Hereafter is represented the total KE according to standard radius, nozzle size and pressure for a 1m height, measurements have been adjusted using a power function:

$$KE_{J/kg} = a \times \Phi^b \times P^c \times R_{\%}^d$$

With Φ : number of nozzle diameter, P: pressure in bar, R: standard radius in %. The parameters are: a=3.213, b=0.531, c=0.132, d=1.245, the coefficient of determination is R^2=0.82.

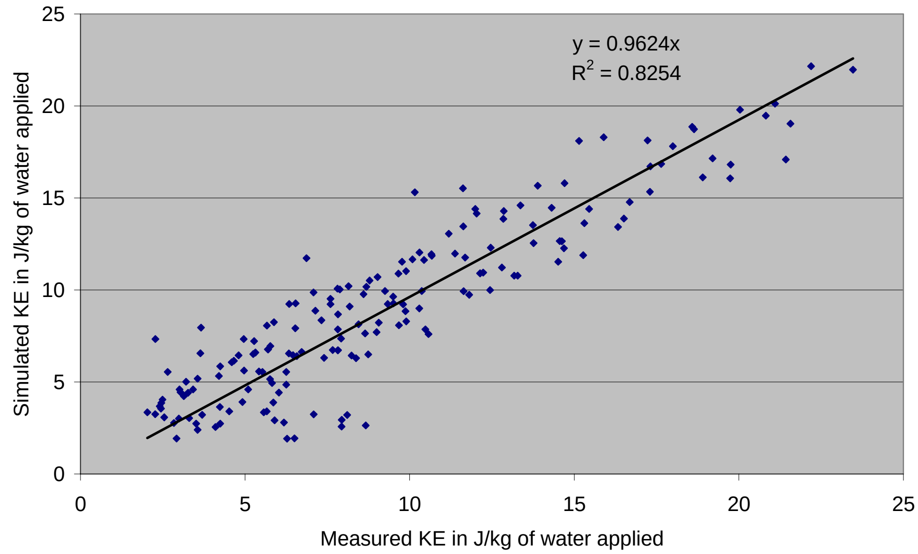


Figure 18. Comparison of KE according to nozzle size, pressure and radius in J/Kg measured and simulated

A number of points are showing high measured values compared to what could be expected. These values which have been measured at different distances, pressures and diameters, don't show any trend. They are probably due to some uncontrolled problems such as: small possible manufacturing default in the deflector, possible rebounds on the sensor frame, or too low number of droplets recorded. These issues will be analysed to improve the measurement protocol.

Evaluation of the overall total Kinetic Energy (KE) J/kg

This value appears to be the best approach to benchmark the overall KE delivered to the soil by a given sprinkler or sprayer type. The values calculated from our measurements are given in Figure 19.

The following remarks can be done:

- Nozzles 11 to 34 exhibit a more or less constant cumulative KE in the range 80 to 200kPa. The increase in maximum radius is compensating the increase in average droplets size. Consequently the operating pressure can be chosen as required from flowrate consideration, yet the cumulated KE will stay constant;
- nozzles 11 and 16 are delivering water with cumulated KE that remain low;
- nozzles 49 has a very different behaviour as cumulative KE increases with pressure. As mentioned before with such a big nozzle the plate is saturated, water is overflowing compared to the potential velocity of water issuing the plate.

It seems that for this type of sprayer, if designed over a maximum flowrate, the distribution characteristics become very bad in terms of KE.

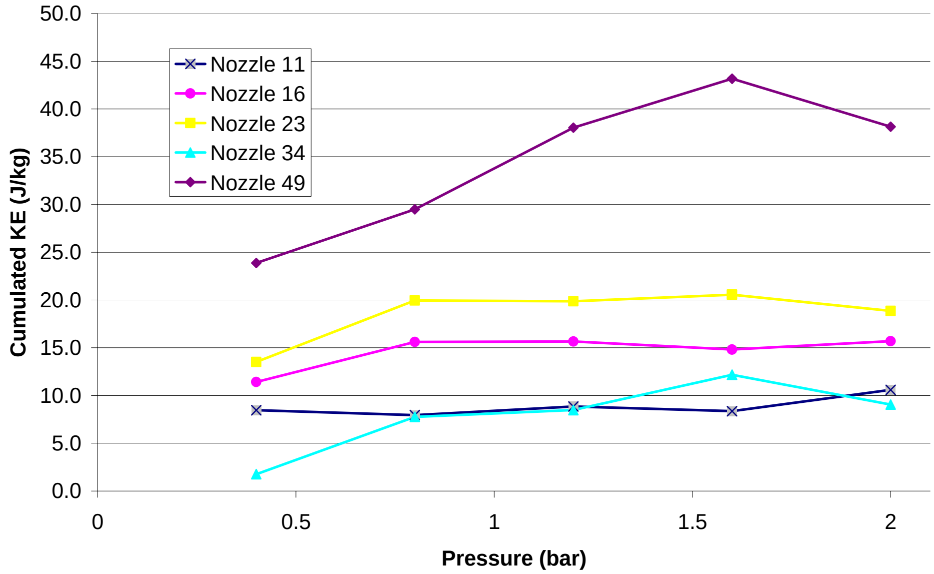


Figure 19. Cumulated KE in J/Kg for the different combinations of KSN

Some comparative values can be found in the literature. For example, with a nozzle 24/128 (equivalent to the #23 of KSN) from Kincaid (1993):

- Nelson Rotator D4, #4.8mm, 1.4bar, KE=24.3 J/Kg;
- Nelson Rotator D4, #4.8mm, 2.1bar, KE=21.3 J/Kg
- Nelson Rotator D6, #4.8mm, 1.4bar, KE=19.3 J/Kg;
- Nelson Rotator D4, #4.8mm, 2.1bar, KE=13.8 J/Kg
- Nelson Spinner D6, #4.8mm, 1.4bar, KE=14.0 J/Kg;
- Nelson Spinner D6, #4.8mm, 2.1bar, KE=11.8 J/Kg
- Nelson Spray I, Flat Plate, #4.8mm, 0.7Psi, 9.0 J/Kg
- Nelson Spray I, Flat Plate, #4.8mm, 2.1Psi, 7.7 J/Kg

A simulated rainfall of 30mm/h delivers 13 J/kg, with droplets of ND50 of 1.4mm (Leguedois, 2003)

CONCLUSIONS AND PERSPECTIVES

Measurements presented here, show that the range of operating and dimensional characteristics, that can influence water distribution parameters is wide for the blue deflection plate. The analytical method allows a consistent representation of these characteristics, compared to the precision required by the calculation of water distribution of a center pivot.

It remains to widen this method to others deflectors (Figure 1) than the blue one used here, to anticipate its generalization.

The method can be used either to qualify emitters in term of distribution characteristics, or to adapt these characteristics to the mechanical capacities of the soil to accept them.
Such characteristics are generally not known by manufacturers, there are sometimes estimated by farmers when they observe the behavior of their soils, especially when pressure is too low.

This analysis of sprayers operation, compared to standard sprinklers, shows that despite sprayers can deliver high average intensities, the overall KE delivered to soil is acceptable by numerous types of soils. This is due to the fact that water is applied in the form of small particles with low cumulated kinetic energy.

We still have to work on the mathematical description of the water distribution of the water. In particular by using the probabilistic method developed by Legat and Molle (2000). This method was based on the principle that a radial water distribution curve is in fact a combination of probability functions describing different populations of droplets diameter distributions according to the distance from the emitter.

The same results can also be used to qualify the sensitivity of distribution to losses by drift and evaporation.

REFERENCES

Delahaye J.-Y., Barthès L., Golé P., Lavergnat J., Vinson J.P., A dual-beam spectropluviometer concept , Journal of Hydrology 2006, 328, pp110-120

ISO-9261 (2004), Agricultural Irrigation equipment – Emitters and Emitting Pipes – Specification and test Methods.

ISO-15886 (2005), Irrigation equipment - Irrigation sprinklers - Part 3: Characterizing of distribution and test methods.

Hendawi, M., Molle, B., Granier, J., Folton, C., Measurement Accuracy Analysis of Sprinkler Irrigation Rainfall in Relation to Collector Shape, JoI&D Eng., Vol.131, 5, 2005.

Kincaid, D.C., (1982), Sprinkler pattern radius, Transaction of the ASAE, p1668-1672.

Kincaid, D.C., (1993), Sprinkler droplets kinetic Energy and erosion potential, ASAE paper 932103.

Leguedois, S., October 2003, Mécanismes de l’érosion diffuse des sols, Modélisation du transfert et de l’évolution granulométrique des fragments de terre erodes, PHD, Inra, University of Orleans.

Le Gat, Y., Molle, B., 2000, Model of Water Application under Pivot Sprinkler, Part 1 : Theoretical grounds, JoI&D, ASCE, vol. 126 (6), p.343.

Molle, B., Characterising Droplet Distribution Of An Irrigation Sprinkler Water Application, ICID congress Montreal, 2002, Question 50-R3-02.

Pruppacher H.R., Pitter R.L., 1971. A semiempirical determination of the shape of cloud and raindrops. J. Atmos. Sci. 28, 86-94.

AN IRRIGATION SUSTAINABILITY ASSESSMENT FRAMEWORK FOR REPORTING ACROSS THE ENVIRONMENTAL-ECONOMIC-SOCIAL SPECTRUM

Evan W. Christen[1]
Nihal S. Jayawardane[2]
Mark Shepheard[3]
Basant Maheshwari[4]
Debbie Atkins[5]
Penny Davidson[6]
Michael Mitchell[7]
Bruce Simmons[8]

ABSTRACT

In order to promote irrigation sustainability through reporting by irrigation water managers around Australia, we have developed an adaptive framework and methodology for improved triple-bottom-line reporting. The Irrigation Sustainability Assessment Framework (ISAF) was developed to provide a comprehensive framework for irrigation sustainability assessment and integrated triple-bottom-line reporting, and is structured to promote voluntary application of this framework across the irrigation industry, with monitoring, assessment and feedback into future planning, in a continual learning process. Used in this manner the framework serves not only as a "*reporting tool*", but also as a "*planning tool*" for introducing innovative technology and as a "*processes implementation tool*" for enhanced adoption of new scientific research findings across the irrigation industry. The ISAF was applied in case studies to selected rural irrigation sector organisations, with modifications to meet their specific interests and future planning.

INTRODUCTION

Worldwide irrigation productivity needs to be increased. Irrigators and water managers need to be encouraged to adopt more efficient and productive irrigation practices. However, it is of paramount importance that such adoption of improved efficiency practices takes place within the context of ensuring long-term environmental, economic and social sustainability. The "Sustainability Challenge Project" of the Co-operative Research Center for Irrigation Futures was developed to understand and promote irrigation sustainability through triple-bottom-line reporting by irrigation water managers around Australia (Christen et al. 2006a). An important aim of the project was to provide an adaptive framework and methodology for improved triple-bottom-line reporting by irrigation organisations, which enhances sustainability on environmental, economic and social issues of concern to the stakeholders. This could be achieved by (a) developing a comprehensive framework for irrigation sustainability assessment

[1]Principal Research Scientist, CSIRO Land and Water, Griffith, NSW, 2680, Australia & Adj. Assoc. Prof. University of New England & project Leader Co-operative Research Center for Irrigation Futures; evan.christen@csiro.au
[2] Principal Research Scientist (retired) CSIRO Land and Water, Canberra, Australia
[3] Post doctoral student, University of New England & Co-operative Res. Center for Irrigation Futures
[4] Associate Professor, University of Western Sydney & Co-operative Research Center Irrigation Futures
[5] Research Officer, University of Western Sydney & Co-operative Research Center for Irrigation Futures
[6] Lecturer, Charles Sturt University & Co-operative Research Center for Irrigation Futures
[7] Post doctoral student, Charles Sturt University & Co-operative Research Center for Irrigation Futures
[8] Senior Lecturer, University of Western Sydney & Co-operative Research Center for Irrigation Futures

and integrated triple-bottom-line reporting, and (b) voluntary application of this framework across the irrigation industry, with monitoring, assessment and feedback into future planning, in a continual learning process. Such complementary applications of the framework thus provide a powerful tool for the communication of the irrigation community's position, contributions and concerns in the current water resource allocation debate. This in turn will allow a more balanced consideration by governments and the community-at-large of the concerns of the irrigation community in the allocation of limited water resources. In the urban irrigation sector, the framework could encourage progress toward more widespread use of sustainability reporting.

The desirable features to incorporate in developing such a voluntary irrigation sustainability assessment framework to guide irrigation water managers current and future practice of annual reporting are:

- Relate directly to irrigation managers interests in increasing irrigation sustainability, and provides for easy adoption in their current reporting practices
- Provide simple guidelines for comprehensive and detailed scientific reporting on irrigation sustainability in their reports, through adoption of the framework guidelines and procedures
- Provide a degree of comparability in reporting across the irrigation sector, which will promote uniformity in structured reporting and also encourage dialogue between stakeholders
- Provide a degree of flexibility for each irrigation manager to adapt to the local conditions and cater for the local regulator reporting needs
- Provide direct link to current and future sustainable management planning and actions
- Relate to standardized international reporting systems like the Global reporting Initiative (GRI) (Global Reporting Initiative, 2002) and their reporting principles, to obtain the benefits of conforming to such systems in complementary usage with the framework
- Accommodate compiling data to a national scale dataset which can be used in scientific lobbying of the irrigation community position, contributions and concerns to the governments and the broad community, in the current water resource allocation debates

In rural irrigation areas, the most suitable reporting units are the geographically well defined entities of irrigation schemes where in Australia annual compliance reporting is a widely prevalent current practice, which could be made more comprehensive by accommodating triple-bottom-line reporting. This paper describes the development of an appropriate framework for rural irrigation.

Triple Bottom Line Reporting

The triple bottom line (TBL) concept provides both a model for understanding sustainability and a system of performance measurement, accounting, auditing and reporting (Elkington 1998, Vanclay 2003). It is generally accepted that the TBL refers to the economic, social and environmental aspects of business performance (Global Reporting Initiative 2002). However, the performance of these three factors should not be viewed in isolation from each other, but as an integrated suite for sustainability, and the broad nature of the three components should not be lost in a narrow indicator definition process that loses sight of the integrated and all encompassing nature of sustainability (Vanclay 2003).

At its core, TBL reporting is a process of developing, monitoring and reporting on indicators of performance across these three spheres seen as vital to the continuation of the enterprise. Because the three spheres are interdependent, a change in one sphere has the potential to impact on the other spheres. This approach allows those involved to reflect on what is occurring within the organisation, its own economy, environment and society but also to consider how the organisation impacts on the economy, society and environment outside

The TBL reporting approach is not only a communication tool, but becomes a part of a process to improve the sustainability of an organisation. A very important aspect of TBL reporting is the underlying iterative process of a learning cycle of planning, taking action, and observing and reflecting upon the result. Through this process, the data collected in the report provides information on which to reflect and develop new directions as required.

In particular, the process of TBL reporting provides an opportunity for the organisation to reflect on its role as part of a larger social system. Identifying the issues that undermine sustainability across the TBL requires input from a breadth of internal and external stakeholders. It establishes a platform for discussing these issues between people that wouldn't normally meet and communicate across boundaries within the organisation and between the organisation and its external stakeholders. Such an exchange provides some level of ownership of the outcomes by staff and the wider community, especially if it extends into deciding what should be done to respond to the issues raised.

A widely used format for the integration of TBL concepts about sustainability into business is provided by the 2002 Global Reporting Initiative (GRI) guidelines. For more information on TBL and GRI potential in irrigation sector see Shepheard et al (2006). These guidelines are used by Australian and international businesses to produce reports that rank highly on the world sustainability reporting stage (SustainAbility et al. 2004). TBL reporting, including the use of GRI format, is increasingly evident in the broader water utility industry (e.g. Sydney Water, City West Water, Melbourne Water, SA Water) and is becoming an important tool to complement sustainability management within irrigation companies (e.g. Murray Irrigation Limited).

Indicator Driven or Objective Driven TBL Reporting?

There is a large volume of literature on activities undertaken in Australia and overseas on sustainable development methodology and the use of indicators. These sustainable development activities have been carried out across a range of agricultural and business sectors, on scales ranging from local, regional to national. Chesson et al. (2000) provides an extensive and critical review of previous work relevant to agriculture, forestry and fisheries in Australia. Ashley et al. (2004) provide a detailed review on sustainability assessment in the water services industries.

The relatively straight forward approach of using a core set of indicators to measure sustainability in specific sectors has a great attraction, which has in recent years led to new initiatives and associated actions across many sectors. However, in dealing with more complex systems like agriculture and fisheries, using core sets of indicators have failed to live up to expectations due to the following characteristics which lead to problems in adoption, as described in a review by Chesson (2002).

There are a number of reasons why this process often fails to develop effective indicator sets. People may be suspicious of the potential use of the indicators, for example, there is concern that indicators may be used in determining the distribution of funds or for regulatory purposes. A specific indicator may not be appropriate in all circumstances. One size rarely fits all and different countries and regions discover that indicators need to be modified to suit their needs. For example, indicators such as length of hedgerows that are appropriate in some European countries have little relevance in Australia. Considerable resources are also needed to collect, collate and report on the indicators. These are difficult to justify when the people being asked to collect the information receive no obvious, short-term benefit. Simple indicator sets have trouble measuring all aspects of human aspirations, or adequately addressing complex concepts. If an indicator set omits aspects that are regarded as important, it is unlikely to receive widespread support."

A more successful approach to measuring sustainability in complex systems is to use a structured approach to identifying the main issues or objectives relating to sustainability, and then address these objectives using selected indicators and performance measures (Chesson et al. 2000). This approach correctly shifts the focus to what the stakeholders want to achieve and the indicators become a means of reporting against the specific objectives. Chesson et al. (2000) and Chesson (2002) proposed a four-step structured approach that addresses all these above-mentioned problems arising from using core sets of sustainability indicators, which increases the chances of broader industry support and adoption, in relation to sustainable development of fisheries in Australia. These four steps in the SCFA (Standing Committee on Fisheries and Aquaculture) method for a national framework for sustainable fisheries are:

STEP ONE: Develop a conceptual framework. The framework should clearly define who or what is being evaluated. It should explore the meaning of 'sustainable development' and articulate our visions and aspirations in achieving it. This would be in the form of an overall objective such as increasing total quality of life.

STEP TWO: Sub-divide the overall objective into successively more specific objectives until we get down to objectives that can be measured. These are operational objectives. Their identification requires extensive consultation involving all stakeholders.

STEP THREE: Identify indicators that address the operational objectives. An indicator often follows fairly easily once an operational objective has been defined. Technical effort is not wasted on indicators that are not relevant.

STEP FOUR: Aggregate indicators at lower levels to form a core set if this is needed for reporting convenience. This does not mean destroying the information at lower levels. Information should remain accessible at whatever level of detail is required".

Once the broad objectives are identified, the subdivision of each broad objective into more specific sub-objectives and operational objectives constitutes a generic component tree. In the SCFA system, each individual fishery which constitutes a reporting unit, then takes the generic component tree as the starting point and tailors it to suit its circumstances. Some components could be expanded and others collapsed. Each fishery can then select the appropriate indicators and performance measures for the chosen operational objectives. Modifying the generic tree and selecting the appropriate indicators and performance measures are undertaken by each fishery, in an open consultative process involving the stakeholders.

AN "IRRIGATION SUSTAINABILITY ASSESSMENT FRAMEWORK" FOR THE IRRIGATION SECTOR

In developing a sustainability assessment system for the irrigation industry, a structured objective-driven approach was adopted and linked to the GRI. An Irrigation Sustainability Assessment Framework (ISAF) was developed to meet the specific characteristics of the irrigation industry (Christen et al. 2006b). The reporting unit can be an irrigation company responsible for providing and managing irrigation water to farmers or an agency with responsibility for urban irrigation activities such as sporting fields. The reporting unit is therefore be a physical entity with a specific geographical region. This allows reporting to be directly linked to management actions by the stakeholders in the area of irrigation.

We propose a structured framework and methodology which has many common features with the SCFA systems. The framework consists of four tiers of sustainability principles, high-level objectives, and generic component trees to define operational objectives, with links to indicators and performance measures. Quantitative indicators should be proposed wherever possible, as discussed in GRI guidelines 2002. As suggested in the SCFA system, each irrigation company can adapt the generic component tree to suit its circumstances in defining the operational objectives, indicators and performance measures. This could involve expanding some subcomponents of the generic tree and collapsing others. The irrigation unit can report against each selected operational objectives, using the indicators to measure performance and the associated management response. Since the ISAF system is designed for use within the rural irrigation sector, at the higher levels the generic tree is likely to be similar for all irrigation companies, while at the lower level they could diverge in response to different local environments. The achievement of common objectives, rather than measurement of common quantities, become the basis for reporting progress (Chesson 2002) and hence are more likely to be accepted by the industry at a national level. Although the ISAF was developed by working with water provider organisations, it is possible to modify the assessment framework for application by other irrigation related organisations. It has also been adapted for the urban irrigation sector (Atkins et al., 2006). We propose a structured framework and methodology which consists of four tiers (Figure 1);

1) Sustainability principles,

2) High-level objectives,

3) Operational objectives, and

4) Indicators and performance measures.

Each water provider company can adapt the generic component tree to suit its circumstances in defining the operational objectives, indicators and performance measures. The water provider companies can report against each selected operational objective, using the indicators to measure performance and the associated management response. Quantitative indicators should be used wherever possible, as discussed in GRI guidelines.

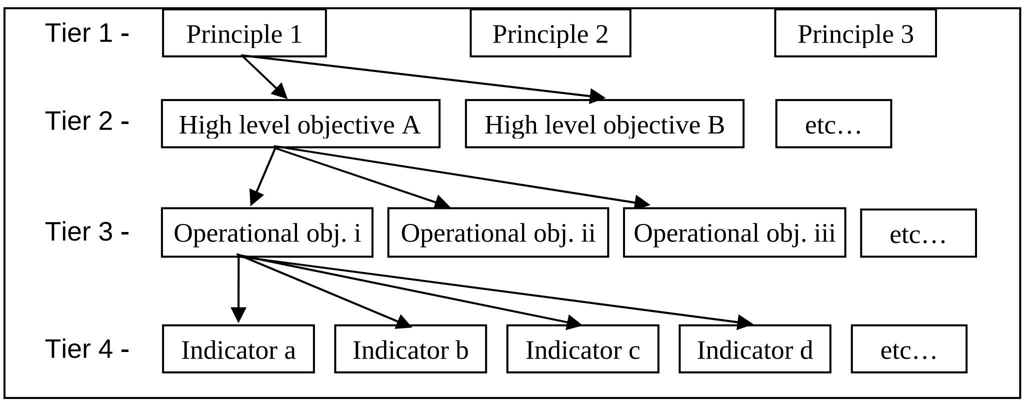


Figure 1. Four tiers of Irrigation Sustainability Assessment Framework (ISAF)

The four tiered ISAF is not intended as a stand alone approach but rather for complementary use and integration into the GRI reporting format, providing the irrigation industry specific context to the generic nature of GRI, whilst retaining the credibility associated with the internationally accepted GRI framework. As such, the ISAF is complementary to the GRI sustainability reporting approach, in providing a more detailed assessment framework on the specific scientific and technological sustainability aspects of the irrigation sector for voluntary compliance reporting. Thus, the tiers in the ISAF can be closely associated with the various levels in the current GRI guidelines, Table 1.

Table 1. ISAF tier levels and associated GRI levels

ISAF Tier level	*Associated GRI level*
1. Sustainability principles	Vision and strategy
2. High-level objectives	Category
3. Operational objectives,	Aspect
4. Sustainability indicators and business performance measures	Performance indicators

Since the ISAF is designed for use within the irrigation sector we expect the sustainability principles to be a shared overarching vision and high-level objectives as shared goals. At the higher levels the generic tree is also likely to be similar for all water provider companies, while at the lower levels they can and will diverge in response to different local environments. For instance, the water provider companies can select their preferred indicators to suit the local monitoring and reporting requirements, thereby providing the appropriate flexibility required to promote voluntary adoption. The achievement of common objectives, rather than measurement of common quantities, become the basis for reporting progress and hence are more likely to be accepted by the industry at a national level.

The sustainability principles that we have developed are based upon Australian accepted definitions of sustainability (Commonwealth of Australia 1992). The National Water Initiative is a joint initiative of Federal and State Governments aiming at sustainable use of water resources in Australia. The National Water Initiative has recognised the continuing national imperative "*to increase the productivity and efficiency of Australia's water use, the need to service rural and urban communities, and to ensure the health of river and groundwater systems by establishing clear pathways to return all systems to environmentally sustainable levels of extraction for irrigation and other uses*" (National Water Commission 2004). This statement directly relates to triple bottom line sustainability associated with our water resources. Based on the above and other nationally accepted sustainability policy directions, our irrigation sustainability principles can be broadly identified as follows:

1. Ensuring the health of river, groundwater and drainage water systems that provide the irrigation water supplies, and maintaining extractions at sustainable levels.

2. Using, conserving and enhancing the land, water and biota resources in the irrigation areas and associated areas, now and into the future.

3. Maintaining and improving the economic benefits and social services to irrigation related rural and urban communities to enhance the quality of life, now and into the future.

We have communicated with Australian water providers and the irrigation industry at large to obtain feedback on these principles as the starting point for a national approach to sustainability reporting and the 1st tier of the ISAF. Selected case studies were used for developing and testing the ISAF, and for obtaining the stakeholder feedback.

Developing High-Level Objectives

The high-level objectives are essentially based on the "broad issues of concern" of the stakeholders, in relation to the environmental, economic and social sustainability of irrigation projects. An iterative process was used to facilitate the development of the high-level objectives for irrigation water providers in Australia, consisting of the following steps:

- Step 1 - Examination of the current annual reports of irrigation companies in Australia and their Land and Water Management Plans (LWMPs) to extract and compile the "broad sustainability issues of concern" of the stakeholders, and an assessment of their subcomponents and their relative importance, to prepare a preliminary listing.

- Step 2 - Circulation of this preliminary listing and the draft procedural guide to key personnel in irrigation companies. Using this feedback to revise this listing and developing the high level objectives in the environmental, economic and social disciplines and in multi-disciplinary areas.
- Step 3 - Seminar presentation and face-to-face discussion on the listing with the irrigation companies and other stakeholders to refine the list.
- Step 4 - Present the high-level objectives list and associated component trees at the pilot case study workshops with the stakeholders to adapt the component trees to local conditions in the irrigation scheme. Use the feedback from case studies to refine the high-level objective list.

Through an examination of the current annual reports of irrigation companies in Australia and their LWMPs the following “broad sustainability issues” of concern to the stakeholders were extracted into a preliminary listing of step 1 above. During a case study conducted with Murrumbidgee Irrigation Ltd (Mitchell et al. 2006) a meeting with staff was held, the participants were requested to provide a list of issues of concern. The issues identified at the meeting were combined with the preliminary listing from the literature, and grouped as follows:

- Water use efficiency and water productivity of irrigated crops (irrigation, drainage, groundwater use, reuse, infra-structure maintenance, irrigation technologies, energy reliance)
- Maintaining healthy landscapes (irrigated lands, wetlands, rivers, watertables, biodiversity)
- Water availability and supply from rivers and ground waters to irrigation schemes, and its seasonal dynamics/politics in meeting the demands of a variety of customers (Living Murray debate)
- Irrigation company governance issues such as finances/resource utilization services/administration/ staff management (communication, safety, training, employment security)/ monitoring and data management services
- Farmers economic performances, water trading opportunities, farm prosperity, markets
- Economic benefits to the region (employment, tourism, value adding industries)
- Irrigation community aspirations in education/health/employment opportunities/ recreation/desirable lifestyles
- Stakeholder engagement/education
- Image of irrigation industry, political significance, risk identification and management

These broad issues of stakeholder concern across the entire environmental-economic-social spectrum were then compiled and re-organised to define the high level objectives under the three disciplinary fields of environmental, economic, social areas. In carrying out the above identification of high level objectives there is flexibility in selecting the number of high level objectives identified to a convenient number, possibly around 10. However, the more important consideration was to ensure that all the issues of concern are adequately addressed within the specified high level objectives. Based on the above listing and subsequent organization under the three disciplines, the high-level objectives were identified and defined through discussions within the research team, as follows:

Environmental/biophysical
(1) Increase water use efficiency/productivity
(2) Protect irrigated lands from adverse environmental impacts
(3) Control degradation of associated water bodies and surrounding environment, and maintain biodiversity
(4) Harmonise irrigation with water supply sources (Enviro-socio-economic)
Economic
(5) Maintain profitability of farm businesses
(6) Improve economic well-being of region and growth in business activity in the region
(7) Improve irrigation company governance (Socio-economic)
Social
(8) Increase well-being and quality of life of farm families (Socio-economic)

It is worthy of note that the workshops undertaken in urban communities identified the same issues with the addition of the availability and use of alternative water sources such as reclaimed sewage effluent. Because of prolonged drought and competition for potable water this emerged as a high priority issue. The high level objectives defined above were also found applicable with minor alterations to the urban context.

Developing generic component trees for specific high-level objectives

There are two basic approaches that could be used in developing the generic component trees for each specified high-level objective. A scientifically based top-down approach could be used, continuing the structured approach of the ISAF. This approach was used in developing the high-level objective of "increasing water use efficiency and water productivity". Alternatively a bottom-up approach could be adopted, utilizing information from selected case studies through the stakeholder consultative and participatory approach to identify operational objectives and indicators. These operational objectives and indicators can then be matched to the appropriate high-level objectives. In addition, we could use a combination of these two approaches. A combined approach was used in developing the component trees of other high-level objectives.

UNDERTAKING TBL REPORTING USING THE ISAF

The following is an example of the steps in developing TBL reports which might be applicable for any organisation, business, group or authority. The steps briefly outline a suggested process but can be adapted as required. Obviously not all steps will be necessary in all circumstances. For example in the urban context irrigation may be only one part of an organizations responsibility, therefore, rather than several workshops, communication may be on an individual basis and may be in a different sequence to that suggested.

The process shown in Table 3 was developed after reflecting on our involvement with rural-based irrigation supply companies as part of our development of the ISAF. If this seems applicable to your situation, we suggest you adapt this approach to best suit your circumstances. Further details on each step are provided below the table.

Getting Started:

1) Determine who the project team is that will be involved in developing TBL reporting in the organisation.
2) Develop an invitation list for an initial goal-setting workshop. The invitation list should be as inclusive as possible.
3) Hold inaugural workshop to outline clear and accepted goals. It is best to have a skilled facilitator run the workshop. At the end you may need to reassess who is part of the TBL reporting project team – both from within the organisation as well as the inclusion of relevant external stakeholders.
4) Project team plans the process for developing the TBL report by studying the Irrigation Sustainability Assessment Framework (ISAF) and other related documentation – such as the Global Reporting Initiative (GRI) guidelines – as well as the current organisational reporting, business plans and the goals determined in the first workshop. In particular, decisions need to be made for the next workshop (step 5) about whether to adopt the sustainability principles and high level objectives in the ISAF as the basis for identifying the issues and objectives for your organisation or for the organisation and its stakeholders to determine your own set of sustainability principles and high level objectives at the workshop that correspond with the suggested four-tier ISAF structure. This may include determining the linkage and/or integration of the ISAF approach with any business plan.

Identify issues and establish objectives:

5) Hold another workshop according to the plans as decided in step 4 to adopt or determine the sustainability principles and high level objectives for the ISAF as adapted for your organisation. This workshop may extend to include a development of component trees of operational objectives or this can be done separately as part of the process of identifying indicators (step 6).

Table 3. Summary of TBL reporting development process for irrigation

Getting started	Sustainability principles	Higher level objectives	Operational objectives	Indicators	Producing and using the report	Stage	Project team	internal stakeholders	external stakeholders
■						1. Determine project team in the organisation (see section 4.3.1).	■		
■						2. Develop an invitation list for an initial goal-setting workshop. (see section 4.3.2).	■		
■						3. Hold inaugural workshop to outline clear and accepted goals (see section 4.3.3).	■	■	■
■						4. Project team plans the process for developing the TBL report	■		
	■	■	▨			5. Hold workshop to adopt or determine the sustainability principles and high level objectives for the ISAF, might include operational objectives	■	■	■
			▨	▨		6. Project team determines OR organises operational objectives into a format that resembles how it will be presented in the TBL report; and develops draft indicators (measures)	■	▨	▨
				▨		7. Workshop to discuss and refine the component trees and indicators and discuss proposed format of the report. Check that organisation staff and external stakeholders don't think anything has been missed. Discuss report format and GRI alignment	■	■	■
					■	8. Draft of TBL report produced and circulated for comment.	■	▨	▨
					■	9. Report finalised, published and circulated.	■		
					■	10. Improving the TBL Report Project team seeks feedback from stakeholders on the published report, and uses this as a basis for reflection to feed into further refining the report content for the subsequent year	■	▨	▨
					■	11. Learning from the TBL report Project team organises internal and external stakeholder opportunities to reflect on the achievements from the past year, and to be involved in problem solving. (see section 4.6)	■	▨	▨

Key:
■ task completion and full responsibility
▨ task may be completed here, partial involvement (it is possible that you choose to involve all stakeholders fully in these stages)

Develop reporting format and select indicators to be used:

6) Project team determines operational objectives or if previously determined as part of the workshop in step 5 organises them into a format that resembles how it will be presented in the TBL report and develops draft indicators (measures) for these operational objectives, a process that may require consultation with experts.

7) Further workshop to discuss and refine the component trees and indicators and discuss proposed format of the report. Check that organisation staff and external stakeholders don't think anything has been missed. Discuss report format and GRI alignment. Discuss plans for how the report will be used to garner feedback and spark a process of continuous improvement and better TBL outcomes.

8) Draft of TBL report produced and circulated for comment.

9) Report finalised, published and circulated.

Use the report, learn from it and develop a cycle of continuous improvement:

10) Improving the TBL Report
Project team seeks feedback from stakeholders on the published report, and uses this as a basis for reflection to feed into further refining the report content for the subsequent year, and how the reporting process will evolve into the future as an ongoing learning cycle leading to continuous improvements in performance.

11) Learning from the TBL report
Project team organises internal and external stakeholder opportunities to reflect on the achievements from the past year, and to be involved in problem solving to whatever extent has been previously determined.

CONCLUSIONS

There is considerable pressure on irrigators and the water supply authorities to improve their performance and to demonstrate their beneficial effects not only in the economic dimension but also in the social and environmental dimensions. The increasing use of a triple bottom line management and reporting arrangement is one way of identifying where improvement can be made and gauging how this is changing over time. There is a desire by the community that businesses/organisations become more responsible and transparent about the sustainability issues over which the business has some influence or impact. This desire for an ethical and accountable approach to business management combines with the drivers of financial value, risk management, compliance with legislation and benchmarking performance to an increase in sustainability reporting by water based and other corporate organisations in Australia across the triple bottom line of economic, environmental and social disciplines.

Through the "Sustainability Challenge" project of the CRC for Irrigation Futures we have proposed an adaptive framework and methodology for improved triple bottom line reporting by irrigation organisations, to enhance sustainability in environmental, economic and social issues of concern to the stakeholders. The proposed framework for irrigation sustainability assessment is complementary to the Global Reporting Initiative sustainability reporting approach, in providing a more detailed assessment framework on the scientific and technological sustainability aspects of the irrigation sector for voluntary compliance reporting.

It is hoped that Irrigation Sustainability Assessment Framework will help irrigation organisations to set triple bottom line sustainability objectives, develop management goals and report performance on achieving these goals. Communicating a more balanced appraisal of the socio-economic benefits and environmental costs of irrigation through triple bottom line reporting, following an accepted international standard, should also engender greater confidence in the wider community regarding the performance and place of irrigation in Australia.

A set of six reports including guidelines for the implementation of TBL reporting in irrigation can be downloaded at the CRC for Irrigation Futures website http://www.irrigationfutures.org.au/

ACKNOWLEDGEMENTS

We acknowledge that this research has been co-funded by the authors home institutions and the CRC for Irrigation Futures. We would like to thank all the case study participants from Murrumbidgee Irrigation Ltd, Murray irrigation Ltd, Coleambally Irrigation Co-operative Ltd , the North and South Burdekin Water Boards and Sydney Councils for their patience and insights.

REFERENCES

Atkins, D., Maheswari, B., Simmons, B. and Mulley, P. (2006). Use of reporting systems to improve the sustainable use of water for urban and peri-urban irrigation. Technical Report No. 03-3/06, Cooperative Research Centre for Irrigation Futures, Toowoomba, Queensland, Australia.

Ashley, R., Blackwood, D., Butler, D., and Jowitt, P. (2004). Sustainable water services – a procedural guide. IWA publishing, London, England.

Chesson, D. (2002). Sustainability indicators – measuring our progress. Science for Decision Makers, September 2002. Bureau of Rural Science, Canberra, Australia.

Commonwealth of Australia (1992). National Strategy for Ecologically Sustainable Development. Australian Government Publishing Service, Canberra.

Council of Australian Governments (1994). Strategic Framework for the Efficient and Sustainable Reform of the Australian Water Industry.

Christen, E.W., Shepheard, M.L., Meyer W.S., Jayawardane, N.S, and Fairweather, H. (2006a). Triple Bottom Line reporting to promote sustainability of irrigation in Australia. *Journal of Irrigation and Drainage Systems.* Vol 20 (4):329-343, November 2006.

Christen, E.W., Shepheard, M., Jayawardane, N., Davidson, P., Mitchell, M., Maheshwari, B., Atkins, D., Fairweather, H., Wolfenden, J. and Simmons, B. (2006b). A guide to triple bottom line reporting as a framework to promote the sustainability of rural and urban irrigation in Australia. Technical Report No. 03-1/06, Cooperative Research Centre for Irrigation Futures, Toowoomba, Queensland, Australia.

Elkington, J. 1998. *Cannibals with forks: the triple bottom line of 21st century business*. New Society Publishers. 2nd edition.

Global Reporting Initiative (GRI), 2002. *Sustainability Reporting Guidelines*. Global Reporting Initiative, Amsterdam, Netherlands.

Mitchell, M., Christen, E.W., Davidson, P., Jayawardane, N., and Shepheard, M. (2006). Embarking on a triple bottom line reporting process with Murrumbidgee Irrigation Pty Ltd. Technical Report No. 03-6/06, Cooperative Research Centre for Irrigation Futures, Toowoomba, Queensland, Australia.

National Water Commission (2004). The National Water Initiative. Document download from the website http://www.nwc.gov.au 18 July 2005.

Shepheard, M., Christen, E.W., Jayawardane, N., Davidson, P., Mitchell, M., Maheshwari, B., Atkins, D., Fairweather, H., Wolfenden, J. and Simmons, B. (2006). The principles and potential benefits of triple bottom line reporting for the Australian irrigation sector. Technical Report No. 03-2/06, Cooperative Research Centre for Irrigation Futures, Toowoomba, Queensland, Australia.

SustainAbility, 2004. *Risk and Opportunity. Best Practice in Non-Financial Reporting*. Standard and Poor's and United Nations Environment Program.

Vanclay, F., 2003. "Experiences from the field of social impact assessment: Where do TBL, EIA and SIA fit in relation to each other?" In *Pritchard, B, Curtis, A Spriggs, J and Le Heron, R. (eds) Social dimensions of the triple bottom line in rural Australia.* Australian Government Bureau of Rural Sciences, Canberra.

PLANNING FOR FUTURE IRRIGATION LANDSCAPES

John Ginnivan[1]

ABSTRACT

In the north of the state of Victoria (Australia), irrigation of agricultural crops accounts for 70% of total annual water use. These irrigation communities are concerned about the sustainability and efficiency of irrigation infrastructure, and the ability of existing infrastructure to meet the needs of future irrigation businesses. At the same time, the broader community is seeking a greater range of services from available water supplies for urban consumption and increased water allocations to improve river and stream health.

To address this crisis in Victoria, a partnership approach has been adopted to support strategic planning initiatives. The partnerships include representatives from: the irrigation community, catchment management authorities, the Victorian State Government and rural water authorities.

Innovative approaches have been developed and adopted to enable irrigation communities to improve water management practices and to formulate sustainable management options for future irrigation landscapes. The approaches have challenged established cultural, environmental, social and economic values and presented both threats and opportunities for irrigation communities and river environments.

This paper will discuss three planning initiatives for future irrigation landscapes:
(1) a regional pilot landscape change project,(2) State Government Legislative reform, (3) the development of reconfiguration plans. Goulburn Murray Water Authority (GMW), in northern Victoria, has offered support and leadership for these initiatives.

BACKGROUND

The Murray Darling System is the largest river system in Australia with a catchment area in excess of 1 million square kilometers and crosses four state boundaries. The river basin begins in Queensland, crosses the length of New South Wales, and then forms the northern border with the State of Victoria and outfalls on the coastline in South Australia. The length of the River Murray from its source to its mouth is about 2500km.

The management of the Murray Darling Basin is underpinned by Commonwealth Government Legislation, namely the ‘River Murray Agreement’. This agreement was ratified in the ‘River Murray Waters Act’ by both the Commonwealth and three State Governments in 1915. The agreement was in the nature of a peace treaty to resolve historical disputes over the use of water sourced from the Murray River.

---

[1] Manager - Salinity, Goulburn-Murray Rural Water Authority. PO Box 264 Kerang, Victoria, Australia 3579; johngi@g-mwater.com.au

Today, the Murray Darling Basin Commission (MDBC), under the auspices of the original ratified agreement, establishes and implements works programs, and facilitates water sharing provisions between the State Governments. All decisions to implement basin actions and works are required to be achieved by consensus between all participating State Governments, including the Australian Capital Territory.

Today the MDBC is facilitating major initiatives in relation to salinity, environmental flows, water quality and biodiversity, to improve natural resource outcomes for the wider basin communities.

A recent and significant basin initiative adopted by the MDBC, 'The Living Murray', seeks to improve the health of the Murray River and its tributary rivers with additional environmental flows. This initiative is the end result of a partnership approach, which has negotiated the vested interests of irrigators, rural communities and the environment. The increased environmental flow allocations will reduce historic water entitlements available to the State Governments and irrigation communities.

In Victoria, the history of irrigation dates back to 1891. The early irrigation trusts, without headwork storages, were unable to guarantee water supplies. Landholders had no obligation to take water, if they did not want it, and were cautious to develop land for irrigation, unless supplies were guaranteed. Insufficient revenue streams for the early Trusts quickly resulted in them becoming insolvent. 'The Relief Act' of 1889 and the 'Water Act' of 1905 wrote off most of the liabilities of the Trusts and largely determined the future of Victorian irrigation for the next eighty years.

For many years, the States managed their respective water businesses without any significant change. However in 1994 all the State Governments agreed to implement programs to facilitate the trading of irrigation water at the farm level.

Irrigated agriculture in the Northern Victorian Region is underpinned by a strong combination of infrastructure and institutional arrangements. Farmers' irrigation water entitlements and associated rights are well established. The reliability of irrigation water is mostly secure and the supply and drainage infrastructure is distributed across all irrigation regions.

Water trading markets now exist for temporary and permanent trading of irrigation water entitlements. Water trading markets continue to provide irrigators with choice and flexibility to manage their water supply, especially at times when difficult drought conditions are present. Between 2002/03 and 2005/06 some 164,248 ML has been traded permanently within and from G-MW irrigation areas, and a further 1,293,000 ML has been traded temporarily across the G-MW region.

Victoria's relatively open water trading regime is resulting in more productive use of water and is generating new enterprises, investment and employment. At the same time, when water leaves an area, the extra delivery costs on the remaining irrigators and the flow on effects to wider communities are issues that need to be addressed.

Since 1994, large volumes of water have been traded from some localities, making it a financial burden on water authorities and their remaining customers, to maintain supply infrastructure and levels of service (Figure 1 – Permanent Transfers of Water Entitlements Cumulative Movement of Entitlements 1991/92 – January 2007).

In instances where irrigation communities are severely impacted upon by permanent loss of water resulting from water trade, water authorities will need to consider phasing out unviable irrigation supply services.

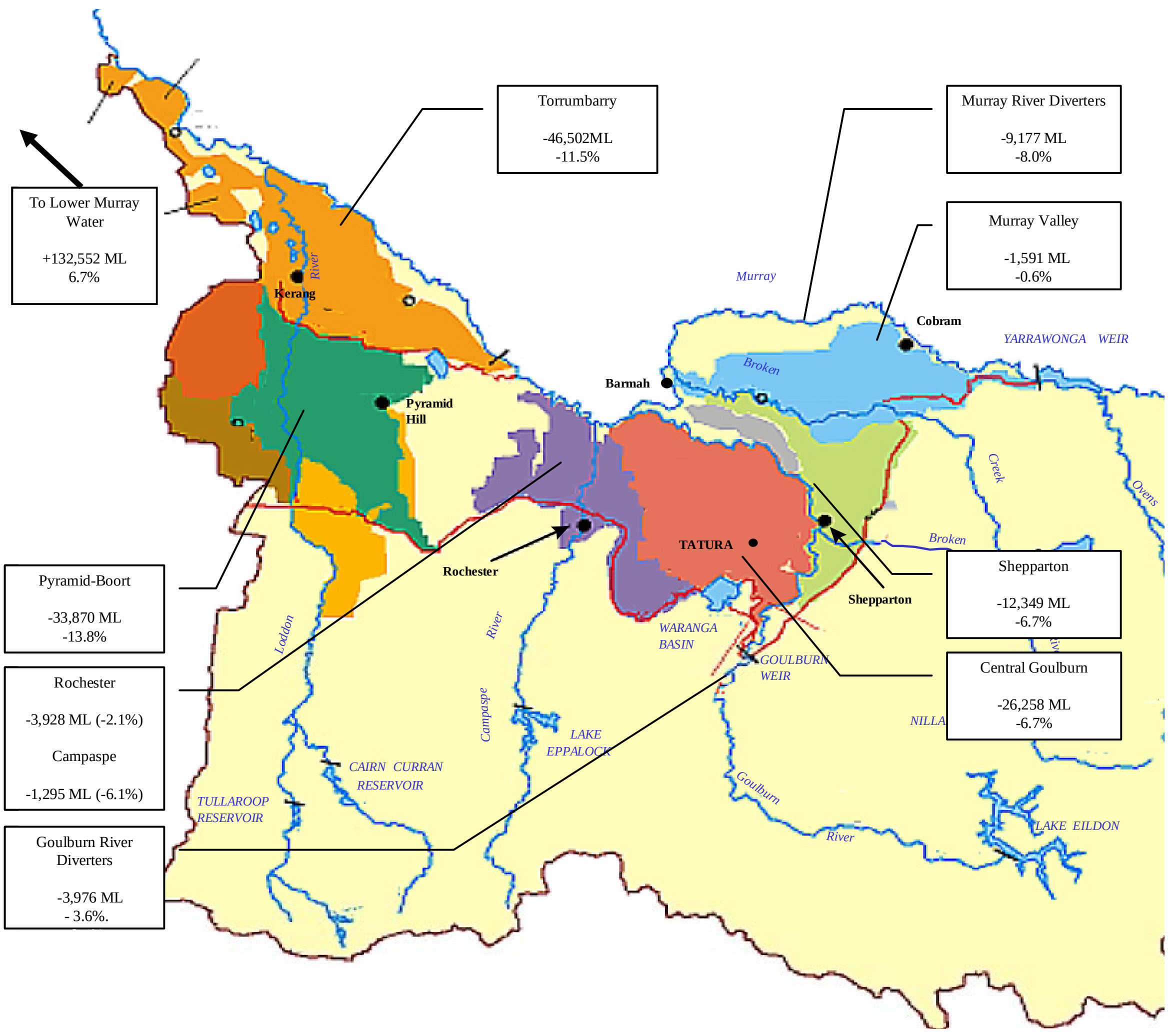


Figure 1. Permanent Transfers of Water Entitlements, Cumulative Movement of Entitlements 1991/92 – January 2007

INTRODUCTION

The combination of temporary and permanent trade within and outside of the six Goulburn-Murray Water districts has already seen some localities trading away up to 40% of their water. Fig 2 graphically demonstrates further the non uniform spatial distribution of permanent water trade.

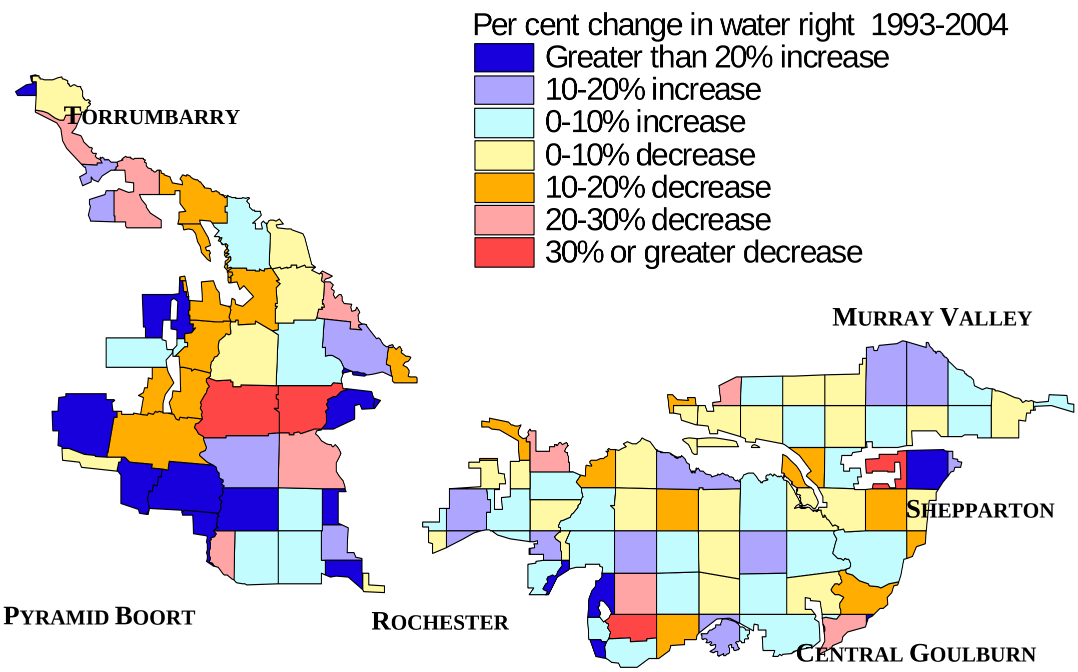


Figure 2. Percent Change in Water Right 1993 - 2004

The delivery of irrigation supplies is primarily undertaken through a large network of open earthen channels which are subject to evaporation and seepage losses, and variable annual maintenance costs.

Photo 1. Typical earthen irrigation supply channel

Photo 2. Typical earthen irrigation supply channel

Photo 3. Low use supply channel infested with weeds

The irrigation industry has been required to respond to significant water reform pressures such as: the increased importance of reducing off farm impacts on the environment, processing and marketing industry restructure, global market pressures and the current severe drought conditions.

In many irrigation areas, some irrigation supply infrastructure is nearing the end of its useful life. This fact, combined with the impacts of permanent water trade out of individual irrigation areas, results in a surplus of infrastructure, and a situation where the annual operation and maintenance costs are being paid by fewer irrigators.

In most irrigation areas, soil types are variable but highly suitable, for a range of irrigated crops and land uses. In many parts of the region, surface drains have been constructed to remove rainfall generated flows and to overcome salinity and water logging constraints. While irrigation property sizes are diverse, and enable the region to be attractive to different irrigated agricultural enterprises, the expansion of individual enterprises can often be constrained due to high capital values assigned to many of the ‘close by’ smaller holdings.

The diversity of irrigated agricultural enterprises results in the region being basically independent of the success of any one industry. Industries processing irrigation products and providing irrigation service support are located in close proximity to the major irrigation areas.

Partnerships between State Government, individual irrigation areas, their dependent communities, businesses and environmental stakeholders have actively commenced to work through the challenges and opportunities with which their regions are presented, in order to support sustainable irrigation landscapes and healthy river and wetland environments.

Consistent with the State Government's 'White Paper', it is proposed that any termination of supply services be done through an agreed process. This requires the water authority preparing, in consultation with affected irrigation customers and regional stakeholders, a 'reconfiguration plan'. Because of differences in scale and community interest, the 'reconfiguration planning' process is flexible.

KERANG-SWAN HILL FUTURE LAND USE PILOT PROJECT

In 2000-2003, a community based working group, together with government agency stakeholders, was charged with the task of choosing a preferred strategic regional development program for the pilot project study area.

The area had been chosen as a 'Pilot" because it shared many of the resource management and landscape change issues that have arisen at the national scale. Those changes occurred as a result of:

- Changing community profiles;
- Agricultural viability and business scale needed;
- Water reform, and impact of water trade on infrastructure;
- Recognition of ecological services;
- Balancing multi-use objectives for waterways with high environmental values;
- Salinity;
- Flooding; and
- Regional development.

The pilot project area is located in the area between the Kerang Weir and Swan Hill (Figure 3), on the western extremity of the Riverine Plain, with Mallee dune fields to the northwest. The location provides a unique mix of soils: the riverine heavy grey and brown cracking clays, suited to pasture and crop growing; the Mallee sandy ridges are suited to horticultural development and dryland agriculture. The area has a diverse range of agricultural industries including: irrigated grazing, dairying, horticultural farms, and dryland grazing and cropping enterprises. The major land use of the study area is mixed irrigation farms (grazing and cropping).

The area is supplied with irrigation water from the River Murray via the Torrumbarry Irrigation System (TIS) which is a linked system of channels and natural carriers, lakes and streams. The TIS was developed from the efforts of many early Irrigation Trusts and expanded later by state water authorities. The legacy of TIS gravity irrigation supply system is that most of the irrigation now undertaken is on the low lying heavier riverine soils, which are less suitable for higher value irrigation. Tresco, which neighbours the pilot area is an exception, and has been developed as a pumped district for horticulture.

The area, while being at the lower end of the Loddon and Avoca catchments, is also ‘mid catchment’ in the sense that it has significant impacts on downstream users on the Murray River.

The pilot project undertook a process of:

- Identifying current land use in the study area;
- Identifying key stake holders;
- Determining land use implications if existing trends continue;
- Identifying the key issues that need to be addressed, if existing trends continue;
- Developing management principles to guide actions or policy;
- Developing future visions and integrated packages to provide an alternative future rather than allowing existing trends to continue; and
- Strategically evaluating the social, environmental and economic consequences of each implementation package developed.

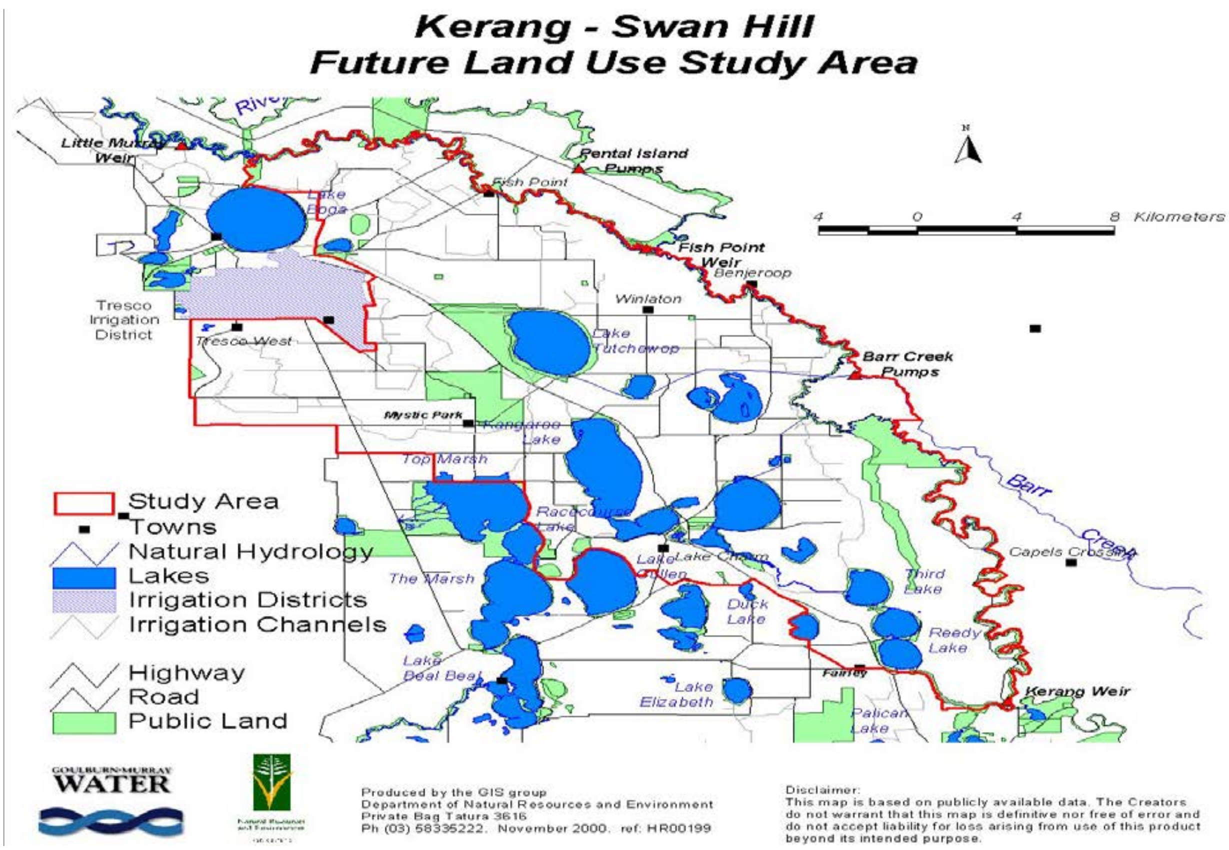


Figure 3. Kerang – Swan Hill Future Land Use Pilot Study Area

The community working group identified the following key management issues, and drivers for change, within the area:

- The economic value of irrigation, from parts of this supply system, is low and diminishing. Permanent water is being sold from the area at a rate of 6% per year and the MDBC cap on irrigation diversions, and introduction of interstate trade, is likely to accelerate this decline;

- Many farmers in the area have chosen to exit irrigation by permanently selling off their water right to higher value horticulture or dairying. This action results in a loss of economic activity to the study area. Those left have to bear a higher percentage of infrastructure costs because exit fees do not currently apply. People are becoming worried about what will happen to the area if this trend continues or accelerates;

- Some of the major components of the irrigation infrastructure are approaching the end of their economic life and will cost tens of millions of dollars to replace;

- The establishment of irrigation supply to a high value horticultural development, directly from the Murray River, has diminished the need to supply water from Torrumbarry Weir and through the key wetlands. The lower dependence on existing supply infrastructure will increase costs for remaining irrigators. The decreased irrigation flows passing through key wetlands have the potential to alter water quality and eventually impact on the Murray River;

- Ongoing expenditure to implement flooding and drainage strategies, to protect former areas of irrigated land from which irrigation water has been permanently traded away, was deemed unsustainable. An option to use some low lying land for increased flood pondage was supported;

- There is a huge concern that the overall health of the River Murray system is in decline and that additional environmental flows may be required to address the decline of ecosystems. Demand for environmental flows to satisfy ecosystem requirements, including those of the internationally recognised ecosystems of the Kerang Lakes, is likely to put more pressure on irrigation supply systems;

- Salt disposal throughout the Kerang Lakes Area has been a long standing issue. Changes to the Torrumbarry system provide new opportunities for improved salinity management such as new drainage reuse areas and salt harvesting operations;

- There is potential for new areas suitable for high value irrigation which are not currently supplied by the irrigation system; and

- Demographic changes are increasing demand for hobby farms and residential blocks of land, particularly near the lakes.

The development and implementation of a land use strategy would provide more certainty for future investment in the area. This is essential for the development of a sound regional economy and a relevant irrigation supply system. With a sound strategy for land use, the area has a good basis for attracting investors, retaining water and growing its economy.

Land, water, environment and community cannot be managed independently of each other; change in one impacts on the other. This is especially true in the Kerang-Swan Hill area, where the lakes have many different functions. The result of this interconnection has been that any explicit plan to change land, water and environmental management is difficult to agree upon. It involves many different aspects, the consequences are difficult to predict and the default option, of maintaining 'status quo' is the path of least resistance.

Changes in land, water and environment are happening by default, without a plan and are unmanaged from a regional point of view. The consequence of this may be acceptable to some, but from a broader community perspective, opportunities are lost. Capturing these opportunities will require considerable courage, from diverse stakeholders, to embrace change and agree upon an explicit plan for the area.

The net result is that it is vital for the area to develop a vision for future irrigation and dryland land use. Also there must be active management of environmental assets in the area so that relevant, integrated and cost effective infrastructure is provided.

The key findings of the pilot project recognised this need, not just within the study area but also in other regions faced with similar environmental management issues and irrigation landscape change.

A brief summary of the management packages developed by the Community Working Group, which are not specifically addressed in reconfiguration programs, are listed below

<u>Property Land Use and Development Package</u> explicitly introduces the concept of paying landholders to provide environmental benefits for the wider community, for which, previously, they have not been adequately reimbursed.

<u>The Regional Development Package</u> was designed to create new opportunities for economic growth and help build community strengths. This would tap into the broader catchment and regional initiatives, including Local Government initiatives. It could cover initiatives for: business development, ecotourism, community development, industry innovation, and development of secondary industry.

<u>The Environmental Services Package</u> was designed to provide payments to landowners who create wider community environmental benefits. This can be for reducing River Murray salinity through using salty water, for creating floodplain storage, for creating carbon credits, for biodiversity assets or other ecosystem services where public benefits are created.

<u>The Land Bank Package</u> was designed to create viable units of land from fragmented under-utilised land parcels, which separately would be unviable. The Land Bank would take unused land offered to it and amalgamate it into viable units for businesses in the Study Area. The

package offered benefits those wishing to retire land from irrigation, and for those wishing to expand.

Regenerating the Lakes Package is a combination of land use planning and water management change designed to create better water quality and services for horticulture, improved environmental outcomes, improved recreational values and possible significant savings in water.

The Floodplain Restoration Package is designed to create extra flood storage and reduce the impact of floods. This involves identifying potential floodplains, reinstating floodplains and the development of management regimes to enhance floodplain diversity. Private landholders would receive payment for environmental services and flooding benefits created.

VICTORIAN STATE GOVERNMENT WATER REFORM

The Victorian Government has maintained a proactive approach to water management issues. The onset of drier conditions and the current serious drought has accelerated the State Government's commitment to both national water initiatives and the new water reforms for urban and rural water authorities. The reforms address growing metropolitan and regional population growth, water trade in irrigation areas, new irrigation developments, and commitments to providing water resources to improve the environment of key rivers and streams including the Murray River. The development of the reforms has been influenced by public opinion that climate change will result in less water being available for all water uses.

In August 2003, the Victorian Government released a discussion paper soliciting wide public comment on a number of proposals to better secure Victoria water resources. This was followed by the release, in June 2004, of the Victorian Government's White Paper that outlined over 100 actions to improve the way in which communities use water and manage water for towns and cities, irrigation and the environment. The White Paper outlined an extensive array of legislative reforms that would be enabled by amending the Water Act 1989

The key components relevant to irrigation landscapes would:

- Establish an Environmental Water Reserve- by reducing the(low reliability) irrigation sales pool available to irrigators by 20%;
- Improve water resource planning and management;
- Create a new unbundled irrigator entitlement to water –with a water share, a water delivery right and obligations and a water-use licence;
- Establish a State Water Register; and
- Establish a process for the reconfiguration of irrigation infrastructure systems.

The legislative reforms have provided irrigators with a level of water supply choices, and irrigation communities have a framework to address landscape change as follows:

- Irrigators to have choice about securing high and medium level water resource shares (formerly called sales). These can be increased or decreased via water trading processes;
- Irrigators to determine the distribution capacity share required for their enterprise;
- Irrigators to have choice to remain attached to an irrigation system in the event that permanent trade away from their land holding is a short term management option; and
- Irrigation communities can develop and implement Irrigation Reconfiguration Plans with Water Authorities and include in those plans, sustainable levels of irrigation infrastructure, subject to appropriate recognition being granted to environmental assets.

The White Paper states that Reconfiguration Planning should proceed as part of a strategic overview of the water authorities' infrastructure assets. The purpose of the Strategic Overview is to provide for a planning framework for making decisions about the relative importance of works being proposed for the different customer areas. The overview will focus on service levels, condition of assets, delivery and maintenance costs, current water usage and trends and future customer expectations.

Subject to the Ministerial approval there is a process to be followed by the water authority in preparing a Reconfiguration Plan. This includes the communication obligations, the development of options, the consideration of stakeholder submissions, and the final recommendations, in those situations, where a water authority is unable to obtain customer agreement with regard to changing irrigation infrastructure and or customer water delivery services. The process is outlined in Figure 4.

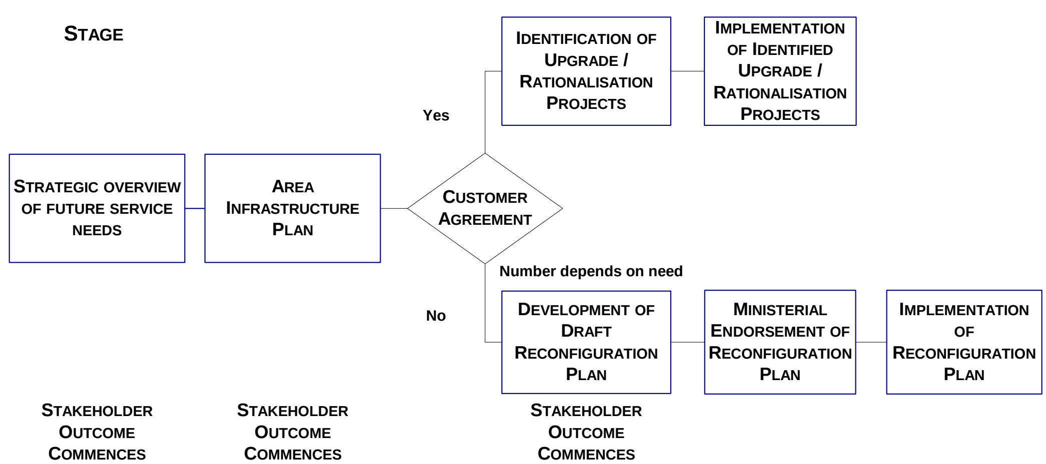


Figure 4. Reconfiguration Process

In return for reducing the sales pool available to irrigators the Government has agreed to fund \$6.0M towards the development of six reconfiguration plans and has requested that G-MW commence the development of reconfiguration plans.

In addition, the Government has agreed that it will co-invest in irrigation reconfiguration programs to recover water for the environment in those areas where this will provide clear benefits to the community and to industry. The initial offer from State Government is a \$50M contribution to recover 25.0 GL of water savings.

Two irrigation areas in Northern Victoria have commenced the development of reconfiguration plans. The Pyramid Boort Reconfiguration Plan is the most advanced.

PYRAMID BOORT FUTURE MANAGEMENT STRATEGY

The Pyramid Boort Irrigation Area, located on the floodplain of the Loddon River, was originally developed with an irrigation supply from the Loddon River in 1886. Some of the existing irrigation supply assets were constructed prior to 1920. The irrigation supply system serves areas of commanded land, on irrigator holdings, via a supply point which records the delivery to each holding.

Currently there are 737 irrigation services (managed as 583 businesses) in the Pyramid Boort Irrigation Area, which is some 150 less than seven years ago. This trend reflects an agriculture-wide trend where economies of scale and increased farm productivity are used to offset diminishing terms of trade impacts. At this time 25% of water rights, tied to original land parcels in the Pyramid Boort Area, have been traded outside the irrigation area or to other lands within the area.

External perception, that parts of the irrigation area should be shut down has diminished the confidence of some irrigators and has curtailed irrigation investment in some areas. In other areas, significant new areas of irrigation have been established with high value enterprises. In combination, these issues drove the need to undertake the ‘Future Management Strategy’ to address the reduced customer base, the spatial shift in demand for irrigation water, stranded irrigation assets, and a need to accelerate asset maintenance works.

While it now appears there is a growing mismatch between the location of irrigation supply infrastructure and where water is needed, the need to change is not driven to any large extent by existing users. However there are opportunities to be captured including distribution costs remaining competitive to attract new development, avoiding expenditure on low use assets, keeping irrigators abreast of technology changes and capturing technology to improve water management efficiency.

Ironically the delivery charges in the Pyramid Boort Area are low compared to other G-MW irrigation delivery businesses. To analyse this anomaly, the Future Management Strategy has identified and partitioned infrastructure costs more accurately by dividing the irrigation supply system into three distinct components i.e. Carriers, Trunks, and Pods (Figure 5)

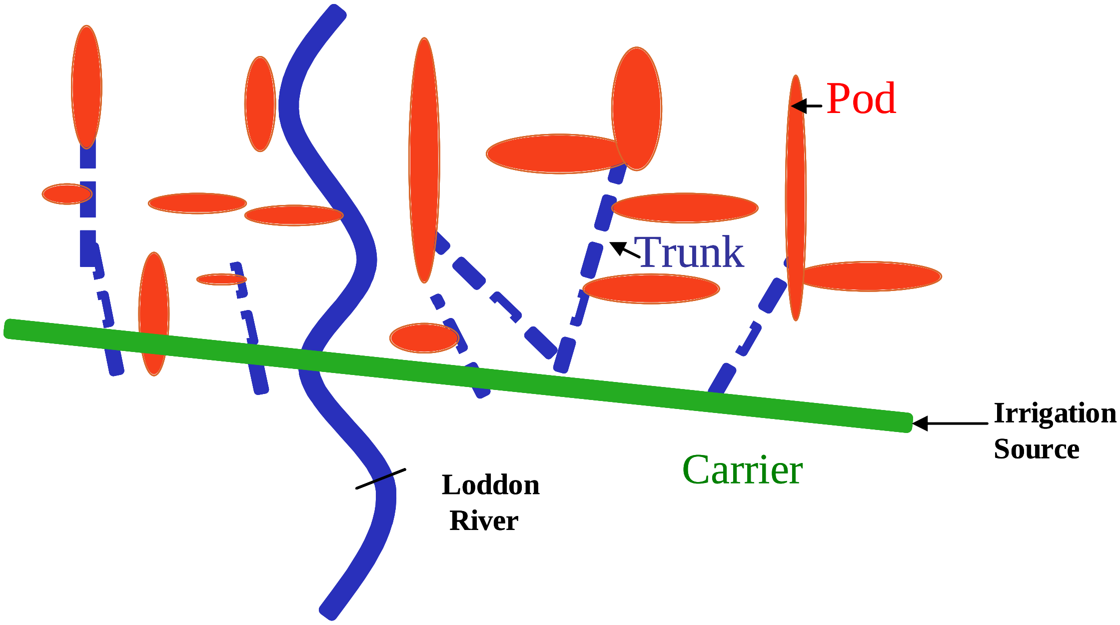


Figure 5. Model of Carriers, Trunks and Pods

It was found that the operational costs of carriers and trunks were reasonable and that these assets could remain as the framework of any new irrigation reconfiguration plan. Within the 32 identified pods, a significant range of operational costs were identified. A key challenge is to reduce the delivery infrastructure costs within the pods.

The Pyramid Boort Future Management Strategy is very much 'a work in progress' and the agreed Vision includes:

- A significant reduction in infrastructure whilst supplying water to those who want it;
- Modernising the supply system with increased efficiency and with operational technology enhancements;
- Encouraging further irrigation development on suitable soils and with due regard for environmental assets;
- Defining and establishing different irrigation delivery service levels; and
- Marketing and communicating the strategy package.

Extensive stakeholder and irrigator customer consultation has occurred throughout the development phase.

THE ROLE OF GOULBURN-MURRAY WATER AUTHORITY

Goulburn Murray Water Authority (G-MW) provides a full cost recovery gravity irrigation and drainage service to 15,000 properties throughout Northern Victoria within six operational areas and unregulated diversion customers. The challenge now is to redesign, reconfigure and refurbish irrigation areas with efficient and affordable delivery infrastructure to support viable irrigation enterprises.

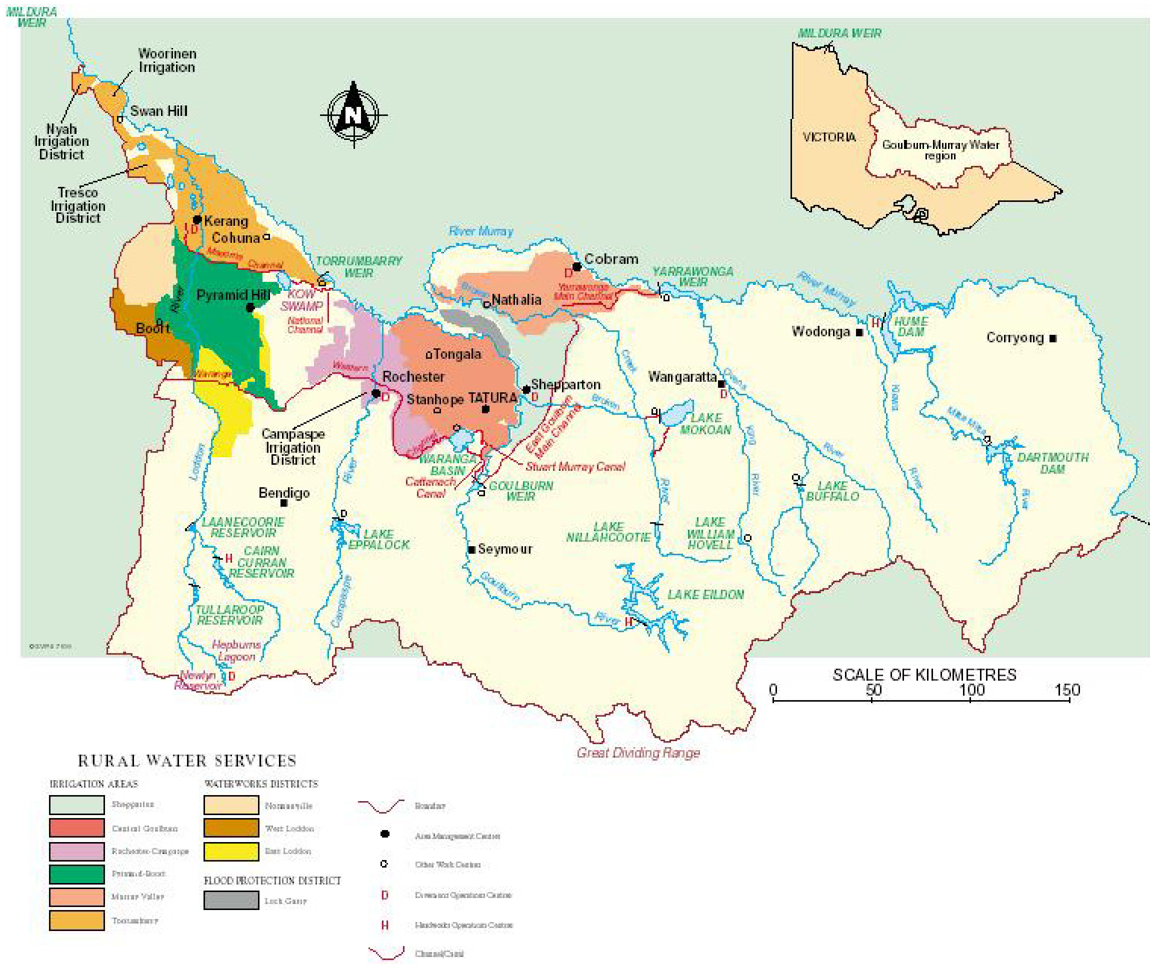


Figure 6. Map of Victoria, Australia showing the operational area of Goulburn-Murray Water

G-MW has a pivotal role in facilitating the development of reconfiguration plans across its customer regions. In response, it has established a small dedicated professional group, to manage, coordinate and implement, six reconfiguration plans with input and support from regional stakeholders including irrigators, catchment management authorities, industry groups, local government and the wider public. Developed plans are referred to the Board of G-MW for implementation approval.

The development of Reconfiguration Plans has included specific requirements for G-MW that include:

- Communications obligations;
- Developing and analysing options;
- Dealing with stakeholder submissions; and
- Developing a draft Reconfiguration Plan.

Part of the preparation work has included the development of ‘a regional atlas’ containing various layers of information (Geographic Information System format) presented in a hard copy to planning participants.

The atlas layers for each irrigation area are divided into the categories of carriers, trunks and pods, irrigation supply asset condition and replacement costs, changes in irrigation activity 1996/97 to 2003/04, enterprise land use, soil groups, important environmental assets, and sites of biological significance.

G-MW has also developed and undertaken a range of asset ‘modernisation’ projects that have resulted in significant benefits, to improve customer service delivery, and secure water savings for the environment.

With information sourced from the ‘regional atlas’, an irrigation ‘modernisation’ proposal has been developed for the Shepparton Irrigation Area, utlising unit costs for a variety of refurbishment works including pipelining channels, channel automation, asset rationalization, and modernised supply metering. The‘modernisation’ business case indicates that 47,000ML will be saved at a capital cost $174M. This information will be an input to the reconfiguration plan process for the Shepparton Irrigation Area.

SUMMARY

The informing aspects from the planning processes include:

- Permanent water trade activity indicates that some serviced irrigation lands are not capable of generating sufficient income returns for irrigators. The consequence is that irrigation delivery infrastructure is underutilized and thus financially supported by a cross-subsidy from other irrigators;

- Regional irrigation communities must change to secure both a sustainable level of irrigation infrastructure, and the delivery of water savings to maintain and enhance the health of environmental assets;

- The effective timing of change is relative to the fact that nothing is likely to be achieved if there is not ‘a shared state of discontent’ between stakeholders;

- Strategic planning and the development of reconfiguration plans are essential, as the ‘do nothing’ approach will guarantee the delivery of sub-optimal outcomes;
- Pilot landscape change projects and planning programs provide support for the development of legislative change and enable the change actions to develop and progress in a confident and orderly manner;
- Rural Water Authorities must be prepared to determine, analyse, and communicate the key business elements of their irrigation delivery charges including the aspects of operation, maintenance, delivery and replacement, and the spatial variances of these within irrigation supply business areas;
- Government, communities and agencies can achieve desired outcomes when working in partnership and with commitment to a common goal. The planning of change must address both needs of irrigators and legislative issues with respect to water management;
- Strategic reconfiguration planning takes considerable time and resources. However the outcomes achieved will probably cost less in the long run to implement and be more aligned to desired social economic and environmental outcomes than a ‘no plan’ scenario;
- Communities need to be given time, support and the tools to effectively participate in planning, the changes required to implement desired reconfiguration outcomes. Furthermore the capacity of communities to participate in change programs must be recognised;
- Information must be presented in spatial formats to improve interpretation and understanding by those participating in the planning process;
- Reconfiguration programs needs to explore concepts whereby irrigation delivery infrastructure enhancements can be integrated with on-farm distribution improvements;
- Where the capital cost of securing water savings from infrastructure upgrades and/or ‘modernisation’ is likely to increase above $5,000/ML, it would be reasonable to expect reconfiguration plans to establish priorities as to where and how any investment strategy could secure multiple benefits (social, economic and environmental) from the delivery of reconfiguration outcomes; and
- For G-MW customers, the future irrigation infrastructure of carriers and trunks is likely to be, within a framework of continuing water trade, servicing suitable irrigation land with minimal off site environmental impacts. This configuration enables expanding irrigation enterprises and larger developers to take advantage of affordable delivery costs, and shorter term agricultural investment opportunities.

REFERENCES

Department of Sustainability and Environment. Victorian Government White Paper ‘Securing Our Water Future Together’ June 2004, Goulburn-Murray Water, Annual Report 2005/06

Goulburn-Murray Water Authority, 2006. Future Management Strategy, Facilitating the Improved Efficiency of the Pyramid Boort Irrigation Area, 2006

Goulburn-Murray Water Authority, 1992. Kerang Lakes Area Salinity Management Plan

Goulburn-Murray Water Authority, 2003. Future Land Use in the Kerang Swan Hill Area

Goulburn-Murray Water Authority, 2006 Torrumbarry Irrigation Area Atlas

Hallows, PJ & Thompson DG, 1995. History of Irrigation in Australia

Wang, Dr. Q J., 2006. Scenarios of the Future: Irrigation in the Goulburn Broken Region Department of Primary Industries, Tatura Victoria

ONE SIZE DOES NOT FIT ALL — RECOGNIZING HETEROGENEITY IN AUSTRALIAN FARMERS

G. Kuehne[1]
H. Bjornlund[1,2]

ABSTRACT

Farmers are heterogeneous, but policy makers are often criticized for treating them as a uniform group. A range of unique factors determine their decision making and their responses to new policy initiatives.

Water scarcity has led to a necessary re-allocation of water among competing users. Provision of water for urban, recreational, and environmental purposes is being done at the expense of the irrigation sector; making it increasingly necessary to encourage effective communication between policymakers and irrigators. The shortcoming of the current one-size-fits-all approach to water management and planning is that it doesn't work for everybody, creating avoidable conflicts between users, compromised outcomes and significant social and community impacts.

Irrigators in Australia's Namoi Valley are facing significant reductions in water entitlements from recent water reforms. An assumption behind the policy is that irrigators are a uniform group who will respond to these reductions in an economically rational fashion. Irrigators have however indicated that they do not intend to behave in this way.

This research explores the influence of farmers' values, attitudes and goals, toward land, water, profit, family, and community on their behavior. Our findings suggest that farmers can be categorized into a typology according to how they associate with three value constructs; *Family Lifestyle* and *Conservation*.

This research will allow policy makers and service providers to communicate better with farmers by using more complementary and more meaningful approaches. The management responses of irrigators are then likely to be more in line with policy expectations reducing the economic, social, environmental, and political impacts of new policy initiatives.

INTRODUCTION

The Namoi Valley in New South Wales (NSW), Australia has a relatively brief history as an irrigation region. Agriculture first began in the mid 1840's when the region was used for the grazing of cattle and sheep along with some wheat production, continuing to the 1960's when the

[1] University of South Australia, Australia; [2]University of Lethbridge, Alberta, Canada,
Geoff Kuehne, University of South Australia, GPO Box 2471, Adelaide, South Australia 5001, Telephone 08 83029188, Facsimile 08 83027001,geoff.kuehne@unisa.edu.au
Henning Bjornlund, University of South Australia, GPO Box 2471, Adelaide, South Australia 5001, Telephone 08 83020064, Facsimile 08 83027001, henning.bjornlund@unisa.edu.au

area was well known for wool production. Irrigation was not very widespread and usually used in drought years or as a way to “finish off” crops (NGMC 2001).

Due to the variability of Australia’s climate large scale irrigation reliant on surface water supplies requires rivers that are regulated. Moves to regulate the Namoi River were taken with the commencement of construction of the 425 GL (345,000 acre-feet) Keepit Dam in 1940. However construction was disrupted by the Second World War and only completed in 1961 (IESC 1969). The dam was built to replace supplies of livestock water previously obtained from declining availability of artesian bore-water; and the authorities had no plans to use it for any other purposes (Kahl 2006).

Up until around 1970, in Australia, the supply of water was in excess of demand (Freebairn 2005) and the price of water was almost zero. It was also suggested that irrigators were slow to take advantage of the water made available from Keepit dam, because of widespread flooding rains between 1949 and 1960 (IESC 1969).

Interest in the potential of cotton growing in Australia had existed from the time of white settlement, but was made more attractive by the financial incentives provided by the government in one form or another between 1951 and 1969 (Pigram 1970). In 1961 Paul Kahl and his neighbour Frank Hadley, two cotton growers from California’s San Joachim Valley, visited several regions in Australia looking for alternative opportunities for cotton growing. Kahl and Hadley settled at Wee Waa in the Lower Namoi Valley and in the 1961-62 season grew the regions first commercial cotton crop (Kahl 2006) using water from the new Keepit Dam.

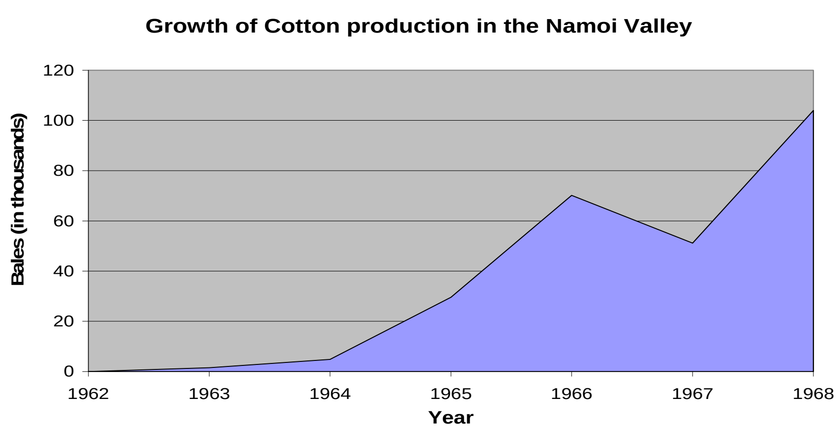


Figure 1: Growth of the cotton industry in the Namoi Valley [adapted from (Pigram 1970)]

Development proceeded quickly, with some fluctuations due to the variability of cotton prices, (See Figure1). Within 7 years there were 65 cotton growers in the valley, with nearly half of them being Americans. In addition to their cotton growing expertise the Americans also brought with them bore construction knowledge and experience and access to technology and capital, (IESC 1969; NGMC 2001; Kahl 2006). The irrigation industry in the Namoi Valley experienced continued growth so that by 2000-01 it covered an area of 119,040 hectares. Of this area approximately 40,000 hectares are irrigated using groundwater depending on seasonal conditions. Cotton accounts for 78% of the total irrigated area but this also varies according to the expected availability of water and the price of cotton relative to the alternative crops that are able to be grown (Powell et al. 2003).

Groundwater was not the preferred source of water due to the cost of pumping, however, the drought of 1965 sparked a vigorous search for groundwater as an alternative to surface water. Groundwater was developed both by those with surface water, who wanted a more reliable supply, and by those without access to surface water. The policy of the NSW Government was to freely allocate licences to extract groundwater even though the total quantity of licences allocated exceeded the renewable resource. It was never considered a possibility that all of the licenses would be activated. This was done before water scarcity emerged, and also at a time when it was considered that exhausting the aquifer was a reasonable policy, at least in the short term, (NGMC 2001). In some ways these actions are understandable as it was the same department that had been responsible for encouraging the use of the water resource from the beginning.

Local irrigators had since the early 1980s warned against the over allocation of groundwater entitlements, and the consequences manifested itself during the drought years of 1992-3 to 1994-5 when it was recognised that the annual aquifer extraction, had increased to almost double the annual average aquifer recharge (Kuehne & Bjornlund 2006b) resulting in falling water tables and in some cases stock and domestic bores that no longer had access to water.

To satisfy the requirements of the national water reforms (CoAG 1994), as well as to counter the effects of the over allocation of entitlements, and in some cases an over extraction of water the NSW Government introduced Water Sharing Plans (WSP). When reducing allocations a decision needed to be made between two methods: i) “history of extraction” (HOE), where those that had demonstrated use over a period of years suffer smaller reduction than those who have been allocated water but have not used it; and ii) “across the board” (ATB) reductions which requires that cuts are made to water entitlements regardless of whether it has actually been used or not. Each method has advantages and disadvantages and impacts licence holders differently depending on how much of their entitlement they have been using.

After much friction in the affected communities and several changes between the two methods of entitlement reduction a decision was made to adopt the HOE method. One of the main reasons for this choice was that it causes less disruption to existing production as it retains more of the productive capacity with those who have developed their land to use their water entitlement (the active irrigators). It was therefore suggested that it will have a smaller socio-economic effect on the communities supported by the local irrigation industry.

It was policy makers expectations that the negative socioeconomic impact of cuts to water entitlements would be reduced by inactive and low value irrigators selling their entitlements to the active and higher valued producers. These expectations are based on the assumption that irrigators make rational economic decisions. However, evidence suggests that this is seldom the case, and that farmers are heterogeneous with different values and attitudes and that these influence the benefits that they derive from using their water. There is therefore evidence that farmers make decision in an attempt to maximize their benefits from using the water taking these various values into account and not simply to maximize their economic gain.

A better understanding of the values and attitudes influencing the Namoi Valley irrigators will provide more reliable indications of their likely management responses to the WSP which can then be used to predict the socio-economic outcome of the reductions in water entitlements. The benefits gained from understanding the components of farmers' heterogeneity will be better designed policy instruments that are more effectively tailored to take into account the different values influencing water users' decision making.

LITERATURE REVIEW

The literature, both within the economics (Gasson & Errington 1993; Fairweather & Keating 1994; Gomez-Limon & Riesgo 2004); psychology (Maybery, Crase & Gullifer 2005); social and health psychology (Conner & Norman 1995); social and community (Vanclay, Mesiti & Howden 1998; Bjornlund 2002); water management (Kuehne & Bjornlund 2006a, b); and farm decision making (Willock et al. 1999) disciplines, suggests that farmers' management responses to any new policy instrument will not be based solely on economically rational decisions but will depend on the values, attitudes and goals of those farmers and their production characteristics.

The study by Maybery et al. (2005) found that three different values determine farmers' response to policy instruments: economic, conservation and lifestyle. They suggest that before introducing new instruments policy makers should understand these values and how they affect the decision making of farmers and therefore affect the final impact of the policy. Bjornlund (2002) found that irrigators in Victoria (Australia) use water markets to achieve three different objectives depending on their position in the structural adjustment process. Gomez-Limon and Riesgo (2004) grouped irrigators in Spain, within a homogeneous area in terms of soil, climate and other factors, and found that their reactions to price changes varied significantly according to the management criteria used in their planning. Kuehne and Bjornlund (2006a; 2006b) found that irrigators in the Namoi region of Australia were planning to make different management decisions in response to a new WSP depending on their perception of themselves as a farmer, either as an investor or as a custodian of the land.

This literature suggests that to determine how farmers are likely to respond to new policy instruments it is important to understand the nature of farming and the values of farmers within the area.

METHODOLOGY

Using the information gained from a mail-out survey and personal interviews (Kuehne & Bjornlund 2006b) the hypothesis was formed that farmers are not homogenous, but that their behaviour is influenced by their values, attitudes and goals towards family, profit, land, water, lifestyle and community. A survey instrument was developed to gather demographic information as well as information on past management actions and future management intentions. The survey also included a set of value and attitude statements against which the respondents were asked to rate their level of agreement using a one to five Likert-scale. A focus group consisting of six agricultural extension professionals was conducted to further refine the values, attitudes and goals statements.

From a potential sample of 478 groundwater licence holders 175 were contacted between November 30th and December 11th 2006. Of these, 34 did not fit the criteria for participation, and 20 refused to participate. The survey was administered to 121 ground water licence holders by telephone. The average length of time taken to complete the 96 questions of the survey was 17 minutes.

One of the limitations of this research is that it creates a typology of a particular group of people that is temporally relevant; it is a construct that describes a group of people at the time of the survey. It may not be transferable to other groups at other times. The way the people respond to surveys is dependent on the influences they experience at that time from the external environment as well as those from their internal environment. For example the statement regarding the willingness to sell water may be influenced by the debate in the media on whether the Australian Government should be able to buy water from irrigators to return it to the environment. Alternatively an irrigator facing financial pressure may be much more inclined to sell water to pay down debts. Each may have a similar long-term view of water but be responding in this instance according to the pressures of the moment. This is not to suggest that the research should be seen as unreliable but rather to suggest that it needs to be repeated in different contexts and at different times.

ANALYSIS

The data was tested for suitability for factor analysis. The KMO measure of sampling adequacy is 0.676 which although not optimal, is still higher than the accepted minimum for factor analysis of 0.5. Bartlett's test of sphericity was used to test the null hypothesis that the variables in the population correlation matrix were uncorrelated (Foster, Barkus & Yavorsky 2005); the significance level of 0.000 allowed the null hypothesis to be rejected. This indicates a strong relationship among the variables and shows that the data is suitable for factor analysis.

Factor analysis was chosen as method of analysis to discover the latent dimensions within the data by summarizing and reducing the data. A small set of variables (three per factor) were combined so that they were able to explain what was common to the larger set of variables in a more concise fashion.

Factor analysis was conducted, (Table 1), using the Principal Axis Factoring extraction method. This correlation-focused approach was used to identify latent constructs and revealed three interpretable factors with eigenvalues of 2.82, 1.62 and 1.36 accounting for 31.4%, 18.0% and 15.1% of the variance respectively. The total variance accounted for by the three factors was 64.6%. Promax rotation with Kaiser normalization was chosen because correlations between factors were large enough that covariance between factors was able to be assumed. Internal consistency reliability was tested using Cronbach's alpha coefficient. The Cronbach’s alpha scores have been described as > 0.9 – Excellent, > 0.8 – Good, > 0.7 – Acceptable, > 0.6 – Questionable, > 0.5 – Poor, and < 0.5 as Unacceptable" (George & Mallery 2003, p. 231). Lower alpha scores for factors 2 and 3 can be explained in part because the number of items per component has a distinct effect on the Cronbach's alpha, (Cortina 1993).

Table 1: Factor analysis results

	Variables	Factor Communalities & Cronbachs' Alphas					
		[a] Com.	alpha	Com.	alpha	Com.	alpha
Factor A	Family should be an integral part of the farming enterprise.	.714	[b].697				
	My family is fully committed to farming as an occupation and way of life.	.718	.715				
	I would like to buy or develop enough land for my family to remain or to become farmers.	.784	.652				
Factor B	People that buy and sell water regularly are just greedy for money.			.645	.636		
	I would never consider selling any of my water unless it was absolutely necessary.			.595	.594		
	If I had unused water I would probably not sell it because it is good drought security.			.720	.527		
Factor C	My most important goal is to leave my land in better condition for future generations.					.544	.584
	I believe that my right to use the water also brings with it a responsibility to use it wisely.					.628	.555
	Farmers should encourage family members to get a good education or develop a skill before deciding on their careers.					.668	.491
Cronbach's Alpha Score			.768		.677		.637

[a] Communalities. [b] Cronbach's Alpha scores if variable removed.

The variables that contribute to Factor A are all related to the family. They reflect respondents' family values and attitudes, and describe how they feel about their family, how they think their family feels about farming, and their goals for future development of their farm with acknowledgement of the family's role in it. We named this value construct "*Family*".
The variables that make up Factor B are related to how the respondents value water. They describe their feelings about water - that it should be retained and not treated as a tradable commodity, that it has a value that is much more than just its economic worth. The important issue is their attitude and values towards it which are ones of "*Conservation*". Variables making up Factor C; are a goal of practicing good land husbandry, a goal of responsible water use, and a concern that family members obtain skills and education before choosing careers. These are some of the values and attitudes expressed by "*Lifestyle*" farmers.

To further analyse the data, Chi-square tests were performed to identify how the 50% of irrigators with the highest factor score on each factor differed significantly from the remaining 50%. For the value statements not included in the three factors see table 2, 3, and 4, for past and future adjustment activities see table 5 and for property characteristics see table 6. To reduce the problem of inadequate cell counts and a tendency for respondents to avoid neutral responses, the five-point Likert scale was collapsed into three categories.

The problem with relying only on those relationships that have statistical significance is that it confuses "statistical significance" with "practical significance". Taken by itself all that statistical significance means is that the same results are likely to occur if the study was repeated, it does not mean that the findings are of any importance (McLean & Ernest 1998). Statistical significance is influenced by sample size which is an indication of the resources available to the researcher. To provide a measure of importance correlations were also performed using Pearson correlation coefficients. Because these are exploratory analyses, the size of the statistical significance was judged to be of lesser importance than the strength of the correlation. DeVaus (2002) claims that social research can accept lower correlation values than the physical sciences, and suggests that the strength of correlations could be interpreted as; 0 to 0.09 trivial, 0.10 to 0.29 low to moderate, 0.30 to 0.49 moderate to substantial, 0.50 to 0.69 substantial to very strong and > 0.70 very strong.

RESULTS & DISCUSSION

The following sections builds a profile of the 50% of irrigators who have the highest factor scores by comparing them to the lowest 50%, for each of the three factors. The discussions are based on the findings reported in tables two to six.

Factor A: Family

Much of what these people do (Table 2) is influenced by the value that they place on family and how they see their family being connected to the family farm. They are firmly focused on their family; they believe that family should be an integral part of the farming enterprise; they want their family members to be closely involved in operating the farm. For them farming is more than just operating a business. They believe that the natural way of things is for their family to be fully committed to farming as an occupation and way of life. Because they would like their family to continue as farmers they are aware that they need to buy or develop enough land to make this achievable.

Because farming is of such importance to them they gain a distinct sense of fulfillment from undertaking farm work. Illustrating the importance they place on growing the farm business, if they needed to make a choice to free up capital they would reduce off-farm investments (even if this meant selling them at a loss) before they would consider reducing the equity that they have in their farm. When making investment decisions they do not search for the best financial returns; instead they will invest profits back into the farm and are unlikely to consider the returns offered by any other alternative investments.

They have a relationship with the land that is beyond the purely economic. They are unlikely to consider selling their farm if it became unprofitable. Although unprofitability is a distinct disadvantage it is not a reason for them to give up. But if a situation arose where they were required to sell land it is most unlikely that they would willingly sell their home block; it has added meaning for them. For these people owning their land also provides them with a sense of security. Because they are aiming to grow their farm businesses for their family members they would be reluctant to sell any unused water but would rather use it to expand their business. Being a member of their community is important for them; they consider that they share the same values and attitudes as others in the community. Their willingness to participate in the community is demonstrated by more of them being members of community-based service organisations such as Lions or Rotary.

Table 2: Other value statements Factor A

	[a] **Value Statements – Family**	Sig.	[b] Means Custodian	Std. Dev.	Means others	Std. Dev.	Correlation with factor scores	Rating of Correlation
Family	Farming is a business	.053	1.20	.546	1.42	.694	-.179	Low-Mod
	Not important for family to continue farming	.000	1.75	.967	2.29	.882	-.285	Low-Mod
	Family should be involved in the farm	.010	2.51	.791	2.04	.902	.267	Low-Mod
Profit	Reduce investments not equity	.002	2.36	.843	1.78	.877	.322	Mod-Subst.
	Always consider alternative investments	.076	2.15	.953	2.50	.808	-.200	Low-Mod
Land	Would never sell the home block	.004	2.00	.938	1.47	.766	.295	Low-Mod
	Owning land provides security	.032	2.81	.536	2.49	.808	.232	Low-Mod
	Sell unprofitable farms	.039	1.95	.964	2.32	.870	-.203	Low-Mod
[c]W	Unused water used to expand	.000	2.53	.812	1.96	.893	.317	Mod-Subst.
[d]C	Community is important	.090	2.73	.660	2.62	.687	.082	Trivial
	Values and attitudes are the same as others	.029	2.78	.555	2.49	.744	.218	Low-Mod
[e]L	Farm work is fulfilling	.001	2.91	.381	2.54	.743	.305	Mod-Subst.

[a] 50% highest of saved factor scores for each component. [b] Rating scale is 1 Strongly disagree through to 5 Strongly agree. [c] Minimum expected cell size violated. [c]Water. [d] Conservation. [e]Lifestyle.

Their property and personal characteristics indicate that these farmers are people who operate considerable commercial businesses (Table 5-6). They operate fewer small farms and are more likely to have large farms. In keeping with a commercial orientation toward farming fewer are smaller users of groundwater but more are larger users. Congruent with a focused and commercial approach to agriculture more are members of farming organisations. More are moderate users of paid farm advice but few are heavy users. Initially this might suggest disinterested or less progressive farmers but it is more likely that it is indicative of the familiarity and expertise they have with agriculture, and that this counters their need for paid farm advice. Because their goal is to develop a successful farm business for their family and combined with larger farms fewer are either able to, or need to, participate in off-farm work.

With an ultimate intention of having the farm business survive through succession to family members more are in the under fifty-five age group while fewer are over fifty five years old. With family succession as such a firmly entrenched goal, passing the farm on to the next generation may happen sooner than for others who may not be so firmly fixed on this type of business succession. A consequence of the desire to ensure that there is a viable farming business to hand on to family is the requirement of obtaining more land. Fewer have sold or leased land

and more have bought or leased more land in the last five years or intend to do so in the next five years. In some cases improving water use efficiency (WUE) can be a viable alternative to purchasing more land. More have improved their WUE in the last five years or intend to do so in the next five years. An allied investment that can assist with improving WUE is the construction of larger water storages which allow the storage of water at times when it is freely available to be used at times when it is more usefully used for production. More have invested in larger water storages in the last five years or are planning to do so in the next five years.

Factor B: Lifestyle

Those who strongly identify with this value construct view their lifestyle as being of prime importance (table 3).

Table 3: Other value statements Factor B

	[a] **Value Statements – Lifestyle**	Sig.	[b] Means Lifestyle	Std. Dev.	Means others	Std. Dev.	Correlation with factor scores	Rating of Correlation
Family	Farming is about business	.001	2.86	.468	2.45	.786	.302	Mod-Subst.
	Family should be involved in the farm	.070	2.45	.832	2.11	.896	.192	Low-Mod
Profit	Financial gain is most important	.015 [c]	1.46	.853	1.27	.635	.125	Low-Mod
	Best to avoid bank finance	.142	2.41	.888	2.08	.971	.178	Low-Mod
	Farming to develop a business	.035	2.23	.927	1.78	.933	.235	Low-Mod
Land	Readily buy and sell land	.163 [c]	1.71	.903	1.81	.974	-.055	Trivial
	Farming is more important than owning land	.158	2.30	.829	2.00	.875	.175	Low-Mod
	Owning land provides security	.086	2.53	.812	2.77	.559	-.169	Low-Mod
	Improving farm increases sale value	.011	2.26	.936	1.78	.914	.253	Low-Mod
[d] W	Sell water at a good price	.008	1.45	.768	1.93	.910	-.278	Low-Mod
Lifestyle	Peace and Quiet is important	.033 [c]	2.95	.286	2.72	.635	.227	Low-Mod
	Farm work is fulfilling	.167	2.83	.492	2.62	.710	.171	Low-Mod

[a] 50% highest of saved factor scores for each component. [b] Rating scale is 1 Strongly disagree through to 5 Strongly agree. [c] Minimum expected cell size violated. [d] Water

Due to this motivation they suggest that people who buy and sell water regularly are just greedy for money. Their intention is to only ever consider selling any of their water as a last resort. They are willing to forgo income that they could have gained from selling or leasing unused water so that they have better security against drought. Being offered a good price for their water is little incentive for them to sell it.

They have what could appear as a contradictory orientation; both valuing lifestyle and at the same time focusing on their farm as a business. Although they think that their family should be involved in the farm, they also suggest that the most important thing about farming is financial gain. Their involvement in farming is done with the aim of developing a business. Their involvement in farming is more important to them than owning land; and they do not believe that owning land gives them a sense of security. Despite this they do gain a sense of fulfillment from farming and enjoyment from the peace and quiet associated with rural living. For them the benefits in making improvements to their farm are not only intangible non-economic rewards but also the building of capital gains.

The production and personal characteristics of these people are of those who might be more oriented to lifestyle benefits. More have smaller farms and fewer have large farms (Table 5-6). Despite their orientation toward the *Lifestyle* value construct they are still commercial farmers and should not be confused with "Lifestyle" or "Hobby" farmers; those people who operate small farms without an expectation of generating a primary income. Perhaps in keeping with landowners who have entered agriculture after other careers fewer are moderate users of paid farm advice and more are heavy users; they apparently recognise the benefits of using the knowledge of others. Fewer are under fifty five years of age and more are over. This could be due to them entering the industry after careers other than farming. This does not appear to be a dynamic category; for example, fewer have bought or leased land, fewer have improved their water use efficiency and many fewer have sold water in the last five years or intend to do so in the next five years.

Factor C: Conservation

Those who strongly identify with this value construct are not primarily motivated by financial gain; instead they express conservation values. This includes an important land husbandry goal aimed at leaving their land in better condition for future generations. In a similar way although they believe that they have a right to use water, they also acknowledge at the same time they have a responsibility to use it wisely. Their belief that water is both a right and a responsibility does not preclude them from selling it when necessary; they don't see a need to keep unused water as drought security. They do not wish for their family to be an integral part of the farm but suggest that it is important for them to get a good education or develop a skill before finally deciding on their careers. They will support family in pursuing work they're good at even if this does not involve agriculture. Financial gain from farming is not their most important incentive; they are motivated by things other than profit. For them owning a farm is more than just an investment. Because they think of it in a way beyond being only used to provide an income they are reluctant buyers and sellers of land. Most of the profit that they generate from their farm business is not re-invested in the farm.

Table 4: Other value statements Factor C

	[a] **Value Statements – Conservation**	Sig.	[b]Means Conserv.	Std. Dev.	Means others	Std. Dev.	Correlation with factor scores	Rating of Correlation
Family	Family should be integral	.127	2.26	.936	2.45	.807	-.110	Low-Mod
	Support family in work they're good at	.082 [c]	2.96	.258	2.881	.532	.174	Low-Mod
	Family members should get a good education	.026 [c]	3.00	.0	2.83	.489	.231	Low-Mod
Profit	Financial gain is most important	.004 [c]	1.15	.515	1.59	.882	-.293	Low-Mod
	Only farming for the financial return	.177 [c]	1.20	.576	1.34	.680	-.115	Low-Mod
	Most money is invested in farm	.131 [c]	2.70	.720	2.83	.522	-.109	Low-Mod
	Owning farm is more than an investment	.176 [c]	2.85	.515	2.67	.700	.144	Low-Mod
Land	Will readily buy and sell land	.163 [c]	1.71	.903	1.81	.974	-.055	Trivial
	Land just provides an income	.130 [c]	1.66	.914	2.01	.974	-.183	Low-Mod
	Goal is to leave land better for the future	.077 [c]	2.98	.129	2.81	.562	.197	Low-Mod
Water	Water is a right & a responsibility	.157 [c]	3.00	.0	2.96	.179	.129	Low-Mod
	Keep unused water for drought	.064	2.53	.812	2.67	.625	-.096	Trivial

[a] 50% highest of saved factor scores for each component. [b] Rating scale is 1 Strongly disagree through to 5 Strongly agree. [c] Minimum expected cell size violated.

The production and personal characteristics of these people suggest that they might be more traditional farmers, undertaking lower valued activities such as irrigated hay production.

Table 5: Actual or intended farm adjustment activities of each value construct

Family	Sig.	[a]Comparisons	Correlation with factor scores	Rating of correlation
Have or will buy or lease more land	.000	More have or will	.327	Mod-Subs.
Have or will improve WUE	.060	More have or will	.158	Low-Mod
Will invest in more water storage	.025	More have or will	.194	Low-Mod
Have or will sell or lease land	.018	Fewer have or will	-.208	Low-Mod
Lifestyle				
Have or will buy or lease land	.038	Fewer have or will	-.178	Low-Mod
Have or will improve WUE	.087	Fewer have or will	-.140	Low-Mod
Have or will sell water	.004	Many fewer have or will	-.261	Low-Mod
Conservation				
Have or will irrigate more	.110	Fewer have or will	-.131	Low-Mod
Have or will sell or lease land	.183	More have or will	.101	Low-Mod
Have or will sell water	.173	More have or will	.106	Low-Mod

[a] Comparison between the 50% of irrigators identifying most strongly and the 50% identifying the least strongly for each respective group.

Fewer have either small or large quantities of groundwater entitlements most have moderate quantities (Table 5-6). Demonstrating an attachment to community they are enthusiastic participants in the activities of service organisations. Being more traditional farmers they are modest users of paid farm advice. Perhaps as an indication of the profitability of their businesses many more engage in off-farm work.

Adding weight to the argument that they have a more traditional focus, their families are likely to have been farming for more than three generations. They are less likely to have successors and appear to be a group that is in decline; fewer have increased the size of irrigated land, more have sold or leased land and more have sold or leased water in the last five years or intend to do so in the next five years.

Table 6: Property characteristics of each value construct

Family	Sig.	[a]Comparisons	Correlation with factor scores	Rating of correlation
Farm size	.131	Fewer small more large farms	.183	Low-Mod
Groundwater entitlements	.199	Fewer small more large amounts of water	.163	Low-Mod
Groundwater usage	.034	Fewer are smaller more are large users	.222	Low-Mod
Flood irrigation area	.167	More are smaller fewer are large flood irrigators	.047	Trivial
Member of farm organisations	.084	More are members	.157	Low-Mod
Member of service organisations	.118	More are members	.125	Low-Mod
Seek paid farm advice	.039	More are moderate users fewer are heavy users	-.178	Low-Mod
Have off-farm work	.028	Fewer participate	.190	Low-Mod
Age group	.158	More under 55 fewer over 55	-.108	Low-Mod
Lifestyle				
Farm size	.197	More small fewer large farms	-.164	Low-Mod
Flood irrigation area	.085	More with no flood irrigation and fewer with over 150 Ha	-.238	Low-Mod
Seek paid farm advice	.074	Fewer moderate users more are heavy users	.182	Low-Mod
Age group	.004	Fewer under 55 more over 55	.256	Low-Mod
Conservation				
Groundwater entitlements	.087	Fewer use small or large quantities most are moderate.	-.040	Trivial
Hay grown	.020	More are hay producers	.242	Low-Mod
Sprinklers	.048	More use sprinklers	.202	Low-Mod
Member of service organisations	.060	More are members	.158	Low-Mod
Seek paid farm advice	.015	More are moderate users fewer are heavy users	-.220	Low-Mod
Have off-farm work	.001	Many more have off-farm work	-.306	Mod- Subs
Generations family farming	.088	More are more than 3 generations	.021	Trivial

[a] Comparison top 50% with bottom 50% of each factor score.

Differences Between Value Constructs

This research has shown that there are differences in the values, attitudes and goals that these farmers hold and that these differences do lead to important variations in their behaviours. We have developed three value constructs; *Family*, for family focused farmers whose prime aim appears to be the continuation of the farm business; *Conservation* for those farmers who are motivated to look after the land and water resource and; *Lifestyle* for those farmers who are attracted to farming for what it offers in terms of lifestyle rewards.

Emtage et al. (2006, p. 88) reviewed the literature on the typologies of Australian farmers and found that most result in “a traditional or conservative type, a smallholder or hobby farmer type, a progressive type, a resource limited type and a comfortable type.” Maybery, Crase & Gullifer (2005) suggest three influences on farmers’ behaviour; economic, conservation and lifestyle. The literature often does not acknowledge the influence of families, although some do find support for the idea that family influences are much stronger than economic. Gasson (1993, p. 112) states, “Rational decisions are made within a framework which embraces intrinsic values in farm work, the values of autonomy and family continuity as well as maximising profitability”. The prime objective for many farm businesses does not appear to be profit maximisation but rather the continuation of the business in the family (Gasson & Errington 1993). Fairweather & Keating (1994) describe three similar styles, the business like dedicated producer, the flexible strategist who tries to balance business and lifestyle and the environmentalist who tries to behave with an environmentally conscious approach, although they also suggest that family is central to all three styles and that profitability is not as prominent as they might have expected.

Irrigators differ in their regard for water according to the value constructs that they associate with. If, for example, in the interest of reform, water is required to be purchased from them, differing approaches will be required. The reluctant water sellers of the *Family* construct are not primarily motivated by profit. Traditional financial incentives are unlikely to be influential. The other reluctant sellers of water; the *Lifestyle* construct view losing their water as diminishing their lifestyle. But on the other hand, because they are also balancing business goals, they could be influenced by a well-presented business case. Those associating with the *Conservation* value construct are not motivated by profit but more so by conservation concerns. Overall these less profitable farmers could be prepared to sell water if they believed it was the “right thing to do”.

CONCLUSIONS

This research has shown that there are between-farmer differences with regard to their values attitudes and goals, that these can be described using a typology and that these differences can be used to predict or explain their behaviour. Further research is required into how these values are formed, how entrenched they are, what would cause them to change, and how likely this is? We also predict that policy instruments that are tailoured to suit the between group variability of farmers identified in this research, and that of others, are more likely to be adopted by farmers as anticipated by policy makers and actual policy outcomes and impacts are therefore also more likely to be aligned with policy expectations.

The alternative to history of extraction reduction, across the board reductions, relied on water being widely traded from inactive to active users of water. The findings in this paper suggest that for this to be successful would require policies to be tailored to suit farmers who are motivated by the value constructs of *Family*, *Conservation* or *Lifestyle*. In the absence of this, the decision of the government to reduce entitlements according to history of extraction was the best choice not on grounds of equity and fairness, or any other criteria, but simply because adjustment through water trading was unlikely to happen with the result that the adjustment process of active irrigators would have been much more difficult and more disruptive to their production increasing the negative socioeconomic impact in the affected communities.

ACKNOWLEDGEMENTS

This research is part of a larger project funded by the Australian Research Council and six industry partners: Murray-Darling Basin Commission, Department of Natural Resources; Department of Sustainability and Environment, Goulburn-Murray Water, Department of Water, Land and Biodiversity Conservation and UpMarket Software Services. Support is also provided by the CRC for Irrigation Futures and the Rural Industries Research and Development. Thanks are also due to the two anonymous reviewers for their comments and insights.

REFERENCES

Bjornlund, H 2002, 'The socio-economic structure of irrigation communities - water markets and the structural adjustment process', *Journal of Rural Society*, vol. 12, no. 2, pp. 123-145.

CoAG 1994, 'Council of Australian Governments' Communique', 25th Feb 94.

Conner, M & Norman, P 1995 *Predicting health behaviour: research and practice with social cognition models*, Open University Press, Buckingham ; Philadelphia.

Cortina, J 1993, 'What is coefficient alpha? An examination of theory and applications', *Journal of Applied Psychology*, vol. 78, no. 1, pp. 98-104.

De Vaus, D 2002, *Surveys in social research*, 5th edn, Allen & Unwin, St. Leonards, N.S.W.

Emtage, N, Herbohnn, J & Harrison, S 2006, 'Landholder typologies used in the development of natural resource management programs in Australia - A review', *Australasian journal of environmental management*, vol. 13, no. 2, pp. 79-94.

Fairweather, J & Keating, N 1994, 'Goals and management styles of New Zealand farmers', *Agricultural systems*, vol. 44, pp. 181-200.

Foster, J, Barkus, E & Yavorsky, C 2005, *Understanding and using advanced statistics: A practical guide for students*, SAGE publications, London.

Freebairn, J 2005, 'Principles and issues for effective Australian water markets', in *The evolution of markets for water: Theory and practice in Australia*, ed. J Bennett, Edward Elgar Publishing Limited, Cheltenham, UK.

Gasson, R & Errington, A 1993, *The farm family business*, CAB International, Wallingford.

George, D & Mallery, P 2003, *SPSS for Windows step by step: a simple guide and reference 11.0 update,* Allyn and Bacon, Boston

Gomez-Limon, J & Riesgo, L 2004, 'Water pricing: analysis of differential impact on heterogenous farmers', *Water resources research*, vol. 40, no. 7, pp. 1-12.

International Engineering Service Consortium 1969, *An economic study of Keepit Dam*, The New South Wales Water Conservation and Irrigation Commission, NSW.

Kahl, P 2006, *Cotton pickin' pioneer*, Paul Kahl, Taren Point, NSW.

Kuehne, G & Bjornlund, H 2006a, 'Custodians' or 'Investors': Classifying irrigators in Australia's Namoi Valley', in *Sustainable Irrigation Management, Technologies and Policies*, eds. G Lorenzinni & C Brebbia, WIT Press, Southampton, pp. 225-235.

Kuehne, G & Bjornlund, H 2006b, 'Frustration, confusion and uncertainty; qualitative responses from Namoi Valley irrigators.' *Water*, vol. 33, no. 4, April 2006, pp. 51-55.

Maybery, D, Crase, L & Gullifer, C 2005, 'Categorising farming values as economic, conservation and lifestyle.' *Journal of Economic Psychology*, no. 26, pp. 59-72.

McLean, J & Ernest, J 1998, 'The role of statistical significance testing in educational research', *Research in the Schools*, vol. 5, no. 2, pp. 15-22.

Namoi groundwater management committee 2001, *Draft water sharing plan for upper and lower Namoi groundwater sources*.

Pigram, J 1970, *Industry in Australia - Cotton*, Longman, Croydon, Vic.

Powell, R, Thompson, D, Chalmers, L, Gabbott, A, Stayner, R & McNeill, J 2003, 'A socio-economic analysis of the impact of the reductions in groundwater allocations in the Namoi Valley -The impact of the Namoi groundwater sharing plan', September

Vanclay, F, Mesiti, L & Howden, P 1998, 'Styles of farming and farming subcultures: appropriate concepts for Australian rural sociology? ' *Rural Society*, vol. 8, no. 2, pp. 85-107.

Willock, J, Deary, I, Edwards-Jones, G, Gibson, G, McGregor, M, Sutherland, A, Dent, J, Morgan, O & Grieve, R 1999, 'The role of attitudes and objectives in farmer decision making: Business and environmentally oriented behaviour in Scotland.' *Journal of Agricultural Economics*, vol. 50, no. 2, May, pp. 286-303.

WATER INFORMATION NETWORKS: INFRASTRUCTURE FOR EFFICIENT MANAGEMENT OF WATER

Iven Mareels[1,2]
Gavin Thoms[4]
Tony Oakes[6]
Su Ki Ooi[3]
Stan Skafidas[5]
John Langford[7]

ABSTRACT

In collaboration with many stakeholders, NICTA, Australia's national information and communications research centre, conducts research in the area of Water Information Networks (WIN). In this project NICTA develops information infrastructure solutions in support of efficient water (distribution) management.

Researchers in WIN, in collaboration with Rubicon Systems Australia Pty Ltd (Rubicon) developed the idea of Total Channel Control™ (TCC™) which is patented and commercialized through Rubicon. TCC™ automates the water distribution management of large scale open canal irrigation networks with the express purpose of achieving greater efficiency. It realizes near on-demand response of gravity fed water distribution networks. As testified by a recent audit of a commercial implementation of TCC™ in the Coleambally irrigation district in New South Wales, Australia, a water distribution efficiency of 90% can be realized. Moreover gains in on-farm efficiency are simultaneously achieved due to the near "on-demand" delivery of water which allows irrigators to significantly modify their irrigation schedules, so as to better suit their local requirements.

At present, WIN researchers in collaboration with the Melbourne based UniWater research centre are considering the joint automation of on-farm irrigation and distribution canals. The goal is to realize that for every drop of water "requested" by the plants in the field, a drop of water is delivered through the distribution network from "reservoir-to-the-plant". The information infrastructure required for such a scheme is discussed.

[1] Professor, WIN Project Leader, National ICT Australia, Victoria Research Laboratory and Department of Electrical and Electronic Engineering, The University of Melbourne, Vic 3010, Australia; i.mareels@unimelb.edu.au
[2] corresponding author
[3] WIN Research Fellow, National ICT Australia, Victoria Research Laboratory, Vic 3010, Australia; skooi@ee.unimelb.edu.au
[4] WIN Project Manager, National ICT Australia, Victoria Research Laboratory, Vic 3010, Australia; gavin.thoms@nicta.com.au
[5] Sensor Networks Project Leader, National ICT Australia, Victoria Research Laboratory, Vic 3010, Australia; stan.skafidas@nicta.com.au
[6] Director, Rubicon Systems Australia, Pty Ltd., 1 Cato Street, Hawthorn East, Vic 3123, Australia; tony.oakes@rubicon.com.au
[7] Professor and Director of UniWater, The University of Melbourne, jlai@umimelb.edu.au

INTRODUCTION

In Australia irrigation accounts for 70% of all fresh water usage [1,2,3,4]. Distribution efficiency, from reservoir to farm gate, is in general poor (variably estimated between 60 to 75% [2,3,4]), not so much due to evaporation and/or seepage losses [2,3], but primarily due to understandably conservative distribution management practices. Indeed to date, undersupply leads to expensive crop losses, whereas oversupply only results in a relatively inexpensive opportunity cost (assuming, perhaps incorrectly, an abundant water supply). This observation clearly identifies the potential of automation and information management to realize efficiency gains, which is at the heart of the present contribution.

In Victoria, Australia, open irrigation canals lose about 10% of conveyed water through seepage and evaporation and about 20% to 30% is lost through bottom-end system outfalls (there are virtually no re-circulation systems in Australia) due to oversupply or is unaccounted for [2,3]. Due to the paucity of appropriate measurement systems, these efficiencies must be considered as guestimates; it is difficult to make precise statements. This too underscores the need for an appropriate information infrastructure. When water is a cheap commodity, there is no motivation to be more efficient in water distribution, but the pressures from population growth, industrialization and climate change [1] are clearly changing this. The need for a more sustainable approach to water management is clearly felt world-wide. Here we discuss an information infrastructure enabling efficient water distribution across large scale irrigation networks. Our discussion is informed by the results achieved with this information infrastructure in the Coleambally Irrigation District, Australia. The annual bulk water license for this district is 620 gigaliter of water. It services nearly 100,000 hectares of farm land and stock water for nearly 300,000 hectares. By December 2007, all 326 control structures operating 481 km of supply canal as well as over 100 on-farm outlets (flows from 15 ML/day to 6,000 ML/day) will be under TCC™ operation. So far, the system under TCC™ has reported a water distribution efficiency of 89% [5]. TCC™ is patented technology [6,7], commercialised through Rubicon. Much of the modelling, control and system theory implemented in this technology has been published [8-16] in the specialised literature.

The paper is organized as follows. We briefly consider the high level requirements for an information infrastructure capable of supporting efficient water management across an entire irrigation district. Next we consider implementation issues, and some of the important side benefits automation brings with it. We underscore the need of integrating the information infrastructure in support of operational management with the overall business information systems to achieve the true potential of the proposed technology. In ongoing work we are developing sensor networks in support of on-farm water management and integrate these into the overall water and economic management of an irrigation district.

WATER INFORMATION NETWORKS

It is clear from an overall systems engineering perspective that water management should happen at the level of an entire water basin, also clearly advocated in [1].

A basic need for the sustainable exploitation of a (water) resource is to be able to account for it in an accurate and timely manner, so that alternative regimes can be appropriately explored and a cost/benefit analysis performed. From a spatial point of view, water volumes in dams/lakes/reservoirs; flows in canals/rivers and flow from borehole/pump infrastructure and water levels in rivers/canals are the basic measurements that are needed to be able to arrive at a mass balance account.

Besides the spatial aspects, we must consider the time scales over which decisions have to be made, or the time scales over which we can expect significant changes in the main variables of interest. Irrigation is not only challenging from a spatial scale point of view, the inherent time scales equally span several orders of magnitude. On the longest time scale (years to decades) the main issue is sustainability: how best to use the limited, renewable water resource. This involves the development of appropriate policy and pricing mechanisms, as well as the appropriate civil infrastructure (dams, canals, recycling plants) and information infrastructure (sensors, actuators, communication network, Supervisory Control and Data Acquisition (SCADA) and data base systems). On a yearly and seasonal basis the allocation of water volumes are to be decided according to specific economic and environmental requirements. Existing civil and information infrastructure must be maintained and upgraded as required. On a weekly and daily basis irrigation schedules are planned to meet farming/cropping needs. In support of this, plant based and soil based sensors, appropriately networked, to monitor crop water needs are ideal. On an hourly time scale individual pools react (water levels and flow change in response to variable demand and in-flow conditions). On the minute time scale, a communication network links canal water levels and flow measurements with the regulating structures to maintain management objectives: water flows over regulating structures, and water levels at specified structures, as well as supply flows to the farm gate and pump flows. Moreover, sensor and actuator variables must be monitored to enable (preventive) maintenance and to ensure a graceful degradation in performance when sensors, actuators, or the communication network develop failures. Proper integration of the information from the fastest time scale to the longest time scale, across the spatial domain of an irrigation district or basin, requires a carefully planned data structure. The longevity and value of the information demands that all measurements are properly labeled and linked with the sensor calibration data. The latter must be kept current, and maintained (sensorML may play an important role here [17]).

Due to the expansive nature of the civil infrastructure, retrofitting or upgrading the existing infrastructure with appropriate sensors, actuators and a (wireless) communication network a solar powered network is appropriate (see for example Figure 1). A level of redundancy in sensor and actuator hardware is ideally required to ensure continued operation under inevitable field failure conditions.

Figure 1 illustrates typical TCC™ hardware, based on the Rubicon FlumeGate™ which acts as both a sensor (for both flow over the gate and water levels on both sides of the gate) as well as a (zero leak) flow regulator. The system is solar powered. A radio network provides communication connectivity between all the units and to a base station, where all the data are collected on a typical report by exception basis (SCADA). Precision manufacturing enables accurate water level sensing as well as accurate flow monitoring (verified to be within +/-2%), a

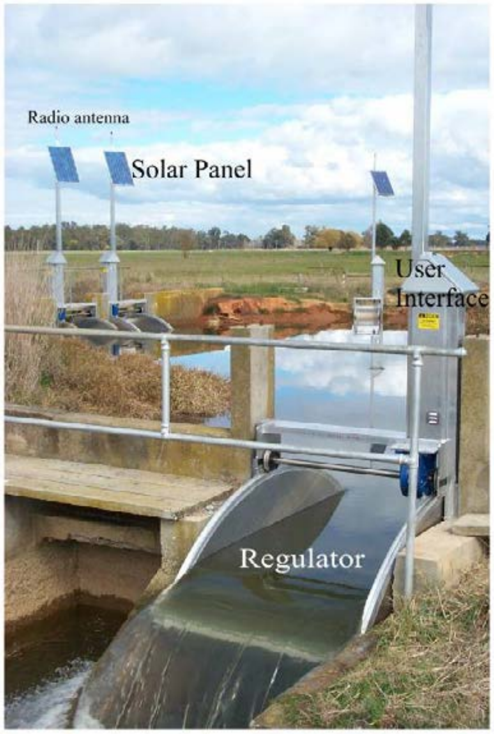


Figure 1. TCC™ hardware in Victoria, Australia

degree of redundancy can be catered for at the level of each structure or at a system design level. This enables a dynamic water balance over the channel network.

As to the spatial density of sensors, and the sampling time to monitor the variables Shannon's sampling criterion applies. Due to the dynamic relations between water flow, gate positions, and water levels, there is inherent dynamical relationship between the spatial and temporal sampling (also implying a level of redundancy). Reporting and data storage are more economically serviced using event or rule based sampling or reporting by exception. In typical Australian irrigation networks sampling rates in the order of minutes at the regulators suffices. Gate/measurement structures should "sample" the canals/rivers at 1 to 10 km resolution to achieve reasonable levels of data for modeling, control and management. Ideally, all variables are stored in a Geo-spatial Information System data base, and linked into the information systems that support the business side of the operation of the irrigation district.

Besides supply monitoring, water usage should also be monitored. (Irrigation losses are typically equally split between distribution and on-farm, indicating that significant gains can be made in on-farm efficiency as well.) Weather station information, soil moisture condition as well as crop stress can be established using a distributed on-farm sensor network. A Zigbee™ based network based on say NICTOR™ (trade mark of NICTA) provides one such solution that we are exploring in Victoria, in the context of dairy, horticulture and viticulture. (See Figure 2.) These data can be gathered to form a true operational picture of the entire irrigation district, enabling forward planning from the farm level to the entire district.

The overall objective is that an information infrastructure as suggested can support through automation and in conjunction with a water market, improved water efficiency and economic gains across an entire irrigation district. Significant economic gains, and a overall water efficiency of 75% are feasible. The cost to realize these savings is minor compared to water buy back schemes, or changing the open channel infrastructure into a piped network.

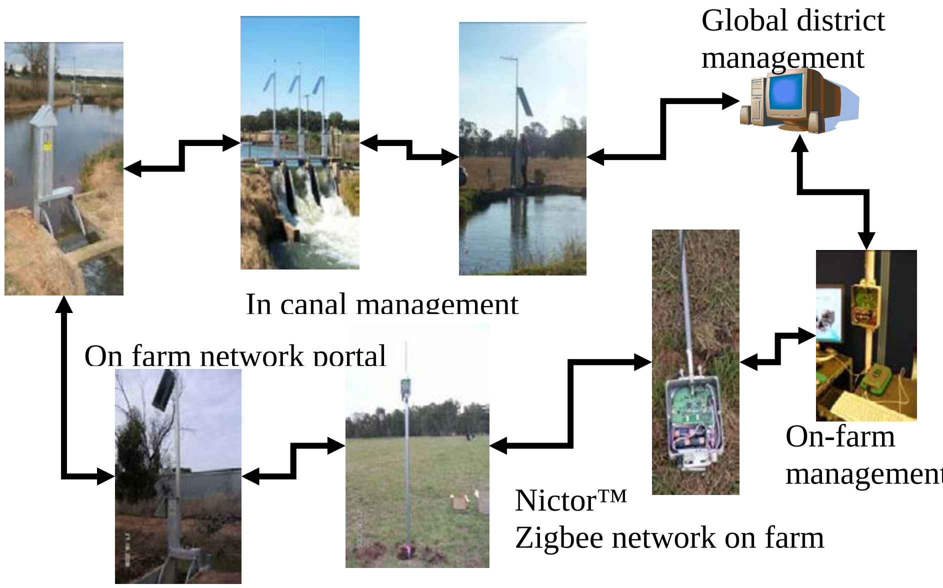


Figure 2: Water managed from "plant-to-reservoir". An information feedback loop in support of sustainable water management (pilot project in Victoria)

WATER INFORMATION NETWORK IMPLEMENTATION ISSUES

One of the great benefits of real time data is the potential to derive a dynamic, quantitatively correct model for the overall water system across the entire irrigation district (see [8,11]). Such a model underpins TCC™ in particular, but more generally any automation of objectives such as water efficiency and water level regulation whilst meeting demand as scheduled. The models also enable scenario simulation and decision support, and can be used for training.

The channel water balance allows one to identify leaks, excessive seepage and evaporation losses, which can be used to inform infrastructure upgrades and maintenance schedules.

Furthermore, automation of channel operation all but eliminates the need for "ditch riders" reducing the CO_2 footprint of the operations as well as alleviating occupational health concerns associated with manual operations of regulators. Automation of on-farm outlets provides similarly life style benefits for the farmer, but more importantly assists demand management and can underpin a better exploitation of the farm resources, and of course it links naturally into billing systems and water trading markets.

Integration of the supply management network with on-farm information networks, and more particularly crop monitoring, open the way to manage water distribution in feedback to crop requirements. Linking the information thus derived with an overall GIS data base would allow long term economic planning of the district, and enable a truly sustainable exploitation of the limited water resource such that the economic return of the available water is maximized within the constraints imposed by the physical infrastructure (reservoirs, canals, etc).

REFERENCES

1. "UNESCO water report", *The United Nations World Water Development Report*, 2003, http://www.unesco.org/water/wwap.
2. ATSE report, {\it Water and the Australian Economy}, April 1999, http://www.atse.org.au/publications /reports/water9.htm
3. Sinclair, Knight \& Merz, {\it Water Savings in Irrigation Distribution Systems}, consulting report commissioned by Goulburn-Murray Water, Australia, 2000.
4. http://www.ourwater.vic.gov.au/ourwater/index.htm, Victoria White Paper
5. *Automated Efficiency*, The Land, Thursday, 26 November 2006
6. I. Mareels, E. Weyer, D. Aughton, Rubicon Research Pty Ltd, *Control Gates, WIPO Number WO02/16698, PCT Number PCT/AU01/01036*
7. I. Mareels, E.Weyer, D. Aughton, Rubicon Systems Australia Pty Ltd, *Fluid Regulation, WIPO Number 02/071163,* Australian Application Number 2002233060, PCT/AU02/00230
8. I. Mareels, E. Weyer, S.-K. Ooi, M. Cantoni, Y. Li and G. Nair, "Systems engineering for irrigation systems: Successes and challenges." Annual Reviews in Control (IFAC), **29**, pp. 191–204, 2005.
9. E. Weyer, "LQ control of an irrigation channel", *Proceedings of the 42th IEEE CDC.* Hawaii, USA., pp. 750–755.
10. Y. Li, M. Cantoni and E. Weyer, "Design of centralised controller for an irrigation channel using H1 loop-shaping", *Proceedings of the Control 2004*. Bath, United Kingdom.
11. E. Weyer, "Control of open water channels", *IEEE Trans on Control Systems Technology*, to appear.
12. E. Weyer, "System identification of an open water channel", *Control Engineering Practise,* **9**, pp. 1289–1299, 2001.
13. S. K., Ooi, M. P. M., Krutzen and E. Weyer,"On physical and data driven modeling of irrigation channels", *Control Engineering Practice*, **13**(4), pp. 461–471, 2003.
14. M. Cantoni, E. Weyer, Y. Li, S. K. Ooi, I. Mareels and M. Ryan, "Control of large-scale irrigation networks." *Special Issue of the Proceedings of the IEEE on the Emerging Technology of Networked Control Systems*, 2007.
15. Y. Li, M. Cantoni and E. Weyer, "On water-level error propagation in controlled irrigation channels", *Proceedings of the 44th IEEE Conference on Decision and Control and European Control Conference ECC 2005*, Seville, Spain, 2005.
16. Stan Skafidas, Iven Mareels, SCADA over ZIGBEE™, *Proceedings USCID 2005*, *SCADA and Related Technologies for Irrigation District Modernization,* Vancouver, Washington, USA, October 2005, pp 79-89
17. http://mail.opengeospatial.org/mailman/listinfo/sensorml

IMPROVING WATER USE EFFICIENCY: THE COLEAMBALLY IRRIGATION AREA MODERNIZATION PROJECT

Mark Nayar[1]
Murray Smith[2]

ABSTRACT

This paper provides an overview of the Coleambally Irrigation Area (CIA) modernization project. The CIA irrigation district is located in the southern Murray-Darling Basin of Australia. The district comprises 477 irrigation farms containing 79,000 ha (hectares) of irrigated land supplied through 700 km of earthen open channel. Development of the CIA modernization project commenced in 2000 with the objective of improving channel conveyance efficiency, reducing operating costs and enhancing water supply services. To date, some AU$16 million (AU$1 ≈ US$0.75) has been expended on capital works for the modernization project. Conveyance efficiency has been improved from 75% before the project, to around 89% in the 05/06 irrigation season saving approximately 60 billion litres of water per year. The cost of the project has been recovered by selling water savings to district irrigators and to government for use as an environmental flow. This paper focuses on two key areas of the modernization project: automation of canal operations and accurate flow measurement in farm turnouts.

INTRODUCTION AND BACKGROUND

Much of the Murray-Darling Basin of southern Australia is experiencing the worst drought on record (MDBC 2007). With increasing water scarcity, improving the efficiency of water resource usage has become a priority issue. As irrigation is a major consumer of water, the minimization of losses in the conveyance of water through irrigation canals has become a key focus of efforts. This paper describes a project undertaken in the Coleambally Irrigation Area in south-eastern Australia to reduce conveyance losses in the district's earthen canal network.

The Coleambally Irrigation Area (CIA) is located in the southern Murray Darling Basin of south-eastern Australia (see Figure 1). Irrigation water is sourced from the Murrumbidgee River, one of the major tributaries of the Murray River. Water supplies are regulated from two major dams with a combined storage capacity of approximately 4,000 GL (Gigalitre or 1 billion litres).

The Coleambally irrigation district was developed over the period 1958 to 1970. The supply system consists of 41 kilometers of main canal, 477 kilometers of supply canal, and a further 734 kilometers of constructed drainage. The system is gravity supplied and the canals are of earthen construction. The commanded irrigation area is 79,000 hectares of which about 35,000 hectares is effectively irrigated. The district contains 477 individual irrigation farms.

---

[1] Water Economist; Marsden Jacob Associates; 683 Burke Rd Camberwell, Victoria, Australia, 3124; mnayar@marsdenjacob.com.au
[2] Chief Executive Officer; Coleambally Irrigation Cooperative Ltd; 7 Brolga Place, Coleambally, NSW, Australia, 2707; msmith@colyirr.com.au

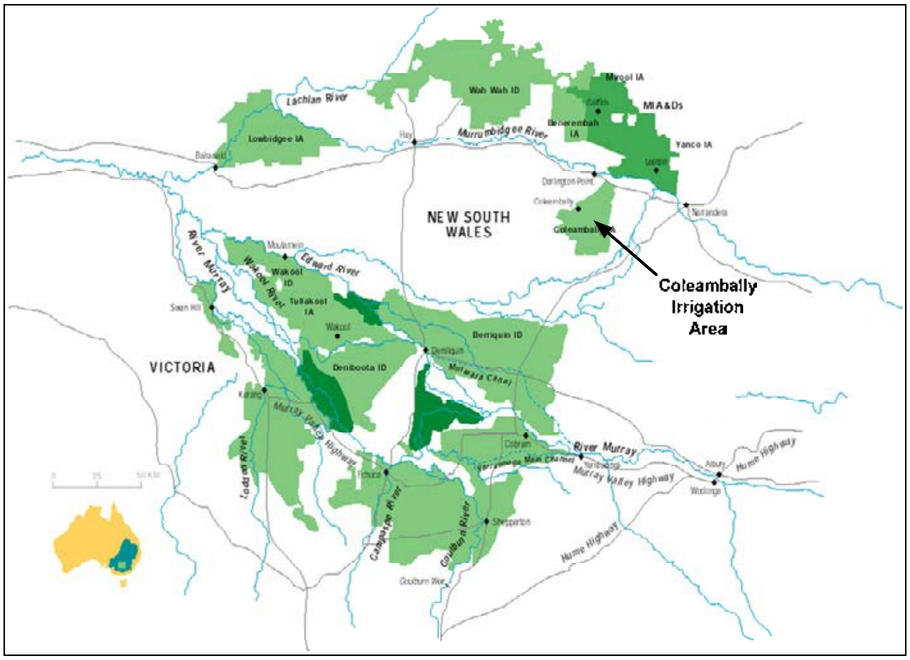


Figure 1. Coleambally Irrigation Area Location Map

The district's surface water license is for a volume of 620 GL per year. This includes a conveyance loss allowance of 130 GL and irrigation water rights of 490 GL. Groundwater pumping accounts for up to 100 GL of usage per year. Water is used to irrigate a range of crops including rice, wheat, barley, oats, canola, soybeans, maize, sunflowers, lucerne, grapes, prunes and pastures. Crops are predominantly flood irrigated although pressurized systems are becoming more common.

The district is owned and operated by the Coleambally Irrigation Cooperative Limited (CICL). CICL is a private co-operative that holds the district irrigation water licence and is responsible for providing irrigation water delivery and associated services to district customers. CICL's focus is the day-to-day operation of the irrigation scheme and the provision of water at the most affordable price to its member customers, consistent with its regulatory obligations and long-term business sustainability objectives.

WATER SCARCITY

Like other irrigation districts in Australia, the CIA is licensed to divert an upper limit or maximum volume of water in any year. The actual volume of diversion into the district varies from year to year depending on water availability from the major storage dams. The state government ministry of water resources determines water allocation or the proportion of the licensed volume of water to be made available to irrigators. Historically, some 90% of CICL's surface water licensed volume, or 550 GL, has been available to the irrigation district on average. However, the introduction of environmental flow rules for the Murrumbidgee River in the late 1990s has resulted in a significant decline in water availability and as a consequence annual diversions from the river (see Figure 2 below). The decline in water availability has been exacerbated in recent years by a succession of low inflows into the major storages due to drought.

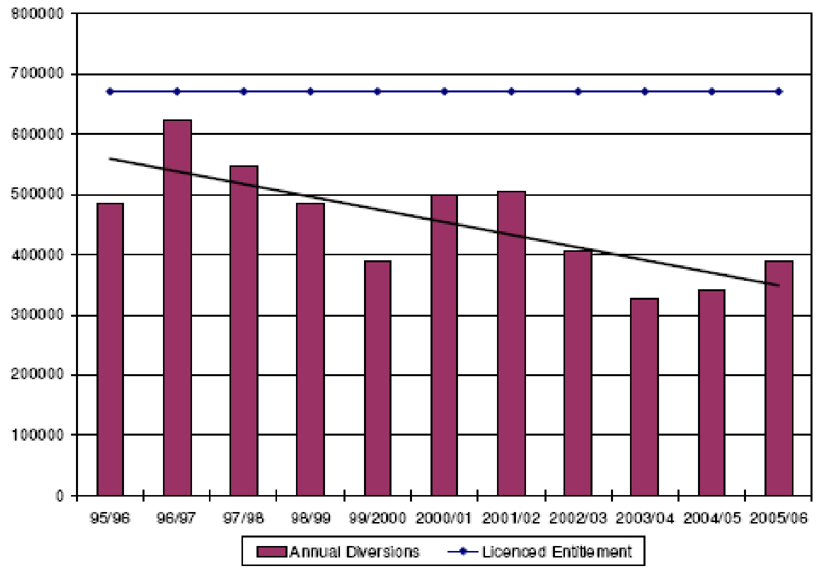


Figure 2. Coleambally Irrigation Area Annual Diversions (ML/year) - 1995/96 to 2005/06

The impact of drought culminated in the current water year with only 10% of the licensed allocation being made available to district irrigators.

CIA MODERNIZATION PROJECT

Faced with a significant reduction in water availability, the Board and management of CICL made the decision to recover the water lost in conveying water through the district canal system to the farm gate. This lead to the development of the Coleambally Irrigation Area Modernization Project, with the objective of raising the efficiency of the conveyance system in order to save water for productive cropping uses.

As a first step, CICL sought to quantify the elements that constitute conveyance system losses (i.e. metering inaccuracy, un-metered diversions, evaporation, seepage, leakage and water theft). This was followed by a comprehensive options analysis which culminated in the development of the modernization project. The main components of the project are:

- canal automation system in 100% of the canal network replacing existing manually operated hydraulic gates and drop board structures;
- accurate water meters in farm turnouts replacing existing Dethridge wheel meters;
- increased maintenance of remaining Dethridge wheels, focusing on improved accuracy;
- metering of smaller uses including stock and tank-fill pipes;
- accurate metering at the district's bulk offtake on the river;
- increased investment in canal seepage/leakage works;
- increased fines and penalties for unauthorised water use (theft); and

- restricting the use of meter outlets to within the rated (accurate) operating range.

The development of the modernization project commenced in 2001. The impact of the project on conveyance efficiency has been marked. Figure 3 below provides a summary of the annual district conveyance loss and delivery efficiency since commencement of the project. CICL's bulk water license includes a component for conveyance losses within the irrigation scheme. The loss licence is on a sliding scale of up to 126,500 ML (Megalitre or 1 million litres) depending on the seasonal allocation. As a result of project works, conveyance efficiency is about 85% compared with 75% previously (see Table 1). In volumetric terms conveyance losses have declined by about 60,000 ML.

Table 1. Coleambally Irrigation Area Conveyance Losses And Efficiency – 2002 TO 2007

Year	Bulk Diversion (ML)	Deliveries (ML)	Conveyance Losses (ML)	Conveyance Efficiency
2002	505,804	405,844	99,960	80%
2003	417,726	307,414	110,312	74%
2004	325,285	235,162	90,123	72%
2005	342,342	234,316	108,026	68%
2006	391,842	349,658	42,184	89%
2007	198,709	167,261	31,448	84%

<u>Project Funding</u>

CICL has been able to offer its customers the 60,000 ML of water savings generated from reduced conveyance losses. This has more than offset the cuts to irrigator water allocations in recent years. CICL has distributed the water savings utilizing four methods:

- sale of water to customers at a fixed price of AU$35/ML per year;
- tendered approximately 11,200 ML of water has been sold by this method at an average price of AU$84/ML per year;
- distributed water to irrigators at no cost in recognition of the exceptional circumstances resulting from drought; and
- provided water free of charge as part of an incentive package to encourage irrigators to adopt a more accurate farm turnout meter.

Also, government has purchased some 3,500 ML of water savings generated by the modernization project for use as environmental flow. This yielded income for the co-operative of AU$1,400/ML.

CANAL NETWORK AUTOMATION

A key component of the Coleambally modernization project is the automation of the canal network with the objective of reducing the operating cost of the canal system, reducing conveyance losses from escapes and improving the ability of the supply system to respond to irrigation demands. The main activities and outcomes of the project are discussed below.

River Offtake and Main Canal Local Automation

Historically, variation in river levels at the district's bulk river offtake lead to variable flow rates in the main canal creating major problems for district water operations. In 2001, the radial gates at the off-take were equipped with upgraded actuators and a Supervisory Control and Data Acquisition (SCADA) system. This allowed CICL to remotely monitor and regulate the flow from the river into the district's main canal. In addition, manually operated gates on eight main canal regulators (a mix of undershot and radial gates) were upgraded with local automation and more robust actuators. These gates were also connected into the SCADA system. The ability to remotely monitor and regulate the main canal resulted in a much improved standard of service to the district's secondary canal offtakes.

Radio Network

Building on the communications system installed for the main canal automation, a district-wide radio network has been implemented to manage the high data transfer rates associated with the planned deployment of automated regulator gates (Total Channel Control). The system provides 100% coverage of the district using broadband radios (Motorola Canopy, E Series and Darcom) It links four major backhaul sites to the base station at the CICL district office. The radio network provides 21 megabits per second (mbps) throughput.

In the future the radio network will provide the backbone supporting low-cost distributed sensor networks on-farm. Indeed, $AU6 million of funding from the Australian government has been secured to implement sensor networks to aid irrigation decision making as part of Stage 2 of the CIA modernisation project. A range of solutions are being investigated for the low-cost radio network including products developed locally (NICTOR and Agrilink).

Figure 3. Repeater Tower: CICL SCADA Radio Network (left) and Canal Regulating Structure Equipped with Automatic Gates (right)

Secondary Canal Local Automation

Stop logs and sluice gates in some 200 secondary and tertiary canal regulating (check and drop) structures have been replaced with automatic gates from Rubicon Systems Pty Ltd. The automatic gate or Flumegate is a bottom hinged overshot gate with an integrated drive mechanism, control console and solar panel power supply. Gate operation is positive actuation in both directions. The deployment of automatic gates in regulators commenced in 2003 and will be completed in 2007.

Computer Control

Progressive deployment of Flumegates allowed traditional manual irrigation planning (scheduling) to be phased out in favour of computer control. The control system used is Total Channel Control (TCC), developed by Rubicon Systems Australia Pty Ltd.

The TCC software system is installed on host computers in the Coleambally district head office. The software system controls the opening and closing of gates automatically in response to irrigation demands and channel levels. The system provides a graphical user interface that allows the user to configure, view and report on the network (see Figure 4). The canal system can be operated manually, in upstream control mode or in fully automatic mode.

The TCC system also features a computerised water ordering system and a demand management system whereby a continual assessment is made of the capacity of the channel network and the ability to supply customer orders. Alarms play a key role in the operation of TCC, with alarms monitoring water levels in each channel pool and the operating status of gates and the communication system. As an outcome of the project, the intensive daily manual planning and operations of the canal system is no longer required.

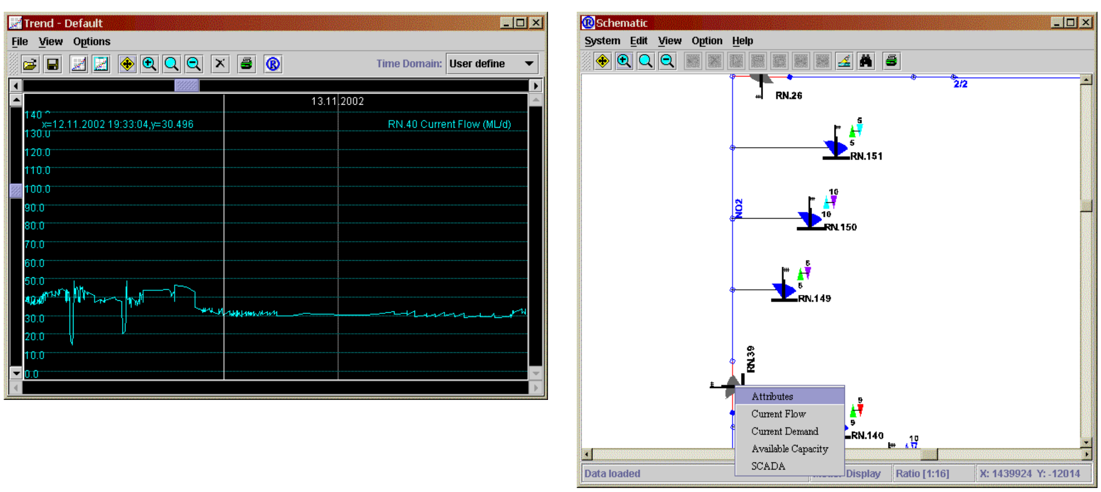


Figure 4. Elements of the Total Channel Control User Interface – Pool water level monitoring (left) and Network schematic (right)

As of 2007, the secondary and tertiary canals are being operated in full automatic mode. Successful deployment of the new technology embodied in the TCC system, however, didn't come easily or quickly, with several years of frustration with TCC caused mainly by problems with the sensor technologies in the automated regulators and tuning parameters associated with automating the regulators. This tested the relationship between CICL and its customers and also the relationship between CICL and the supplier.

Reduced Overflow Losses

Historically, the district's canals were operated at slightly above ordered flow rates in order to ensure customer water orders were delivered in line with expectations. As a result, the canals continuously overflowed into the district drains. CICL effectively lost the escaped water as it was debited against the district's water allocation for that year. The introduction of automated channel operations greatly reduced the overflow during periods of normal operations (see Figure 5). No trade-off in reduced irrigation customer service levels was required to achieve this outcome. Indeed the TCC system has reduced fluctuations in canal water levels and improved the stability of flow rates at farm turnouts. The reduction in overflow volumes is also reflected in improvements in district conveyance efficiency.

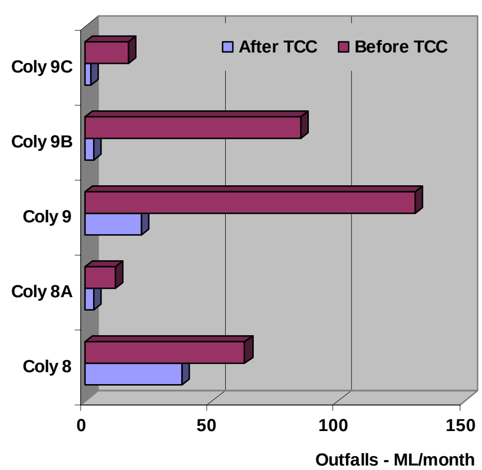


Figure 5. Monthly Volume of Overflow Water – Before and After TCC Automation – Coleambally Irrigation Area

Further tuning of TCC has now completely eliminated all overflows.

Customer Water Ordering

In common with many other gravity irrigation districts, the practice within the Coleambally area is to supply water in response to customer water orders. Up to the late 1980s, irrigators placed written water orders in roadside boxes which were collected by a water bailiff and subsequently processed in the CICL central office. In the early 1990's, written orders were replaced by telephone ordering using an answering machine. In 1999, the answering machine system was replaced with an IVR (interactive voice response) system that enabled touchtone and voice input of orders directly to a water ordering computer database. In 2003, a web site was set up for water ordering. Irrigation customers currently use both the web site and IVR. The advantage of the web site is it is easier to use than the IVR. In addition, irrigators can easily access water account and meter reading information from the website.

Reduced Operating Costs

The full cost of operating the canal system is recovered from the water charges levied by CICL on its customers. Prior to the deployment of the modernization project, the CICL employed 11 water bailiffs and two water planning officers for day to day canal operations. Staff numbers have subsequently been reduced to four customer service officers and one technology officer. The use of automatic gates has eliminated the need for heavy, manual handling of stop-logs in regulating structures (see Figure 6 below). This has significantly reduced the district's workers compensation risks (back, limb and joint injuries). Eliminating the need for a water bailiff to visit every regulator in the canal network at least once a day has markedly reduced fuel, vehicle and access track maintenance costs.

Figure 6. Manipulating Stop Logs in a Canal Regulator – Goulburn-Murray Irrigation District

Improved Customer Service

The automation of canal regulators has allowed the district to introduce almost on-demand water ordering. The time lag between the irrigator posting a water order and actual delivery of the water to the farm turnout has been reduced from 4 days to two hours.

FARM TURNOUT WATER METERING

Improving farm turn-out metering is the second element of the modernisation project. Prior to the modernisation project, the volume of water supplied to farm turnouts in the Coleambally district was metered using a Dethridge wheel (see Figure 7 below). The Dethridge wheel consists of a wheel with vanes, a flume like concrete emplacement, a pendant counting device and an upstream control sliding gate. Dethridge wheels are the basis for customer water billing and the water accounting in many Australian irrigation districts.

Dethridge wheels are relatively cheap, mechanically robust, produce small head losses and can pass debris. However, it has a number of weaknesses. One of the major weaknesses is inaccurate flow measurement as a result of excessive clearances and worn bearings and vanes. Wear and tear to the meter invalidates the calibration curve used to link the rotation of the wheel to the volume of water passed.

Figure 7. Dethridge Wheel Farm Turnout Meter – Goulburn-Murray Irrigation District

Another weakness of the Dethridge wheel in terms of accurate measurement include: irrigators using low flow rates outside the meter's rated operating range and drowning or submergence of the meter due to high tailwater levels. In-situ volumetric testing of Dethridge meters by CICL has shown that on average the devices under recorded in favor of the irrigator by approximately 19% of the actual rate. Of particular concern was the wide dispersion in measurement error with some wheels under recording by up to 30% and others over recorded by up to 20%.

Various options were considered for rectifying the measurement accuracy problems in Dethridge wheels including re-calibrating the wheel rating curve to remove the bias in favor of the irrigator. To implement a changed rating would require replacement of the pendant counter in the wheel. This option was assessed as being the least cost option but was rejected as it was deemed unfair to customers who currently have relatively accurate wheels. CICL were also concerned that the concept of correcting the rating in the wheel would be difficult for customers to understand and accept.

The option of equipping Dethridge wheels with upstream and downstream level sensors with continuous recording was also considered. Level sensors could be attached to the emplacement to improve the accuracy of the rating curve. This option was rejected for several reasons including: 1. undertaking sufficient testing to developing a new rating curve was considered problematic; 2. level sensors attached to walls and their electronics were not considered tamper proof; and 3. the cost of sufficiently accurate level sensors was high.

Increasing maintenance as a means of improving Dethridge wheel accuracy was also examined. This would involve increasing the rate and frequency of bearing and propeller maintenance thus reducing the incidence of excessive clearances and inaccurate wheels. CICL rejected the improved maintenance option on the basis that it was unlikely to provide a long term solution as experience had shown that over time priorities change and the importance of maintenance can be lost.
After consideration of the options CICL elected to tackle the problem of inaccurate Dethridge wheels in a two staged approach. First rules were implemented prohibiting the use of Dethridge wheels at inaccurate low flow rates of below 4 ML/day. Second, it was decided that all Dethridge wheels would progressively be replaced with modern accurate meters. Apart from reducing conveyance losses, CICL's decision recognised that modern accurate water meters improved canal network operations and provided critical information to assist irrigators make better irrigation decisions based on real time information about flow rates and water useage. The pending introduction of national standards for irrigation water meters also influenced the decision to replace wheels. (NMI 2006)

For the water meter replacement program, CICL elected to trial a number of different meter types and configurations in order to identify the preferred meter replacement option. This process was greatly assisted by the work undertaken by the Australian National Committee on Irrigation and Drainage (ANCID 2002) to guide industry on the selection of water meters to replace the Dethridge Wheels. An overview of water meters trialled by CICL is provided below.

Propeller Meter

Propeller meters installed in pipes were first considered as a Dethridge wheel replacement in the mid 1990s. The meter transducer consists of a metal or plastic propeller mounted in a pipe. The pipe section is kept full by inverting the pipe. The co-operative trialled propeller meters from a range of vendors including products from Elster Metering and Water Specialities. Practical experience with the propeller meter showed that while the device was accurate it was susceptible to tampering as well as fouling due to the presence of aquatic weeds in the water supply. Tampering included placement of a steel stake in the pipe to stop the propeller and placing a sack over the propeller to slow down its rotation. It was found propeller meters needed constant inspection and maintenance to remove weeds and check for tampering and spindle wear.

Doppler Meter

CICL has trialled Doppler ultrasonic meters as a replacement for Dethridge wheels. Locally, Doppler meters are widely used, especially in irrigation pumping installations. For irrigation turnouts, the typical meter installation comprises a Doppler transducer mounted in a concrete pipe connected to an electronics housing and solar power unit. The Doppler meter was found to be robust and accurate. The major advantages of the Doppler meter over the Dethridge wheel include: no moving parts to be maintained, minimal obstruction to the flow, ease of installation, tamper proof characteristics of the sensor and comprehensive diagnostics provided in the meter electronics.

Source: www.mace.com.au

Figure 8. Doppler Meter - Transducer (left) and Turnout Emplacement (right)

While the Doppler meter installation proved to be satisfactory in most instances, the accuracy of the meter was affected by water quality. CICL found that on occasions the water supply contained insufficient particles in the water to reflect the meter's signals. This typically occurred in the latter part of the irrigation season when there is little tributary inflow into the Murrumbidgee River and the water supply in the district is sourced from dam releases. Despite the advantages of the Doppler meter, CICL elected not to install any further examples of this meter in its gravity supply area. In contrast to Coleambally's experience, other irrigation districts in the Murrumbidgee Valley have successfully installed several thousand Doppler meters in farm turnouts.

Electromagnetic Meter

As an outcome of the ANCID review of Dethridge wheel replacements, a number of meter vendors developed Electromagnetic (EM) meter emplacements to replace Dethridge wheels. The challenge was to build an EM meter that could handle the harsh environment and be powered using batteries and solar cells. A meter vendor, Tyco Environmental, developed a meter specifically for use in farm turnouts – the Tyco Irriflow. The meter is available either as a full bore meter in sizes 450mm and 600mm, or a specially designed insert for an existing Dethridge Wheel emplacement. The meter is fabricated in stainless steel and is designed to be fully submerged.

The Tyco meter has been used in various installations. The most popular arrangement is to mount the full bore meter to the downstream end of a pipe and enclosed in a pit to ensure a full pipe and equipped with a gate for flow control (see Figure 9). A major advantage of locating the meter at the end of the pit is the ease of access and inspection.

Figure 9. Tyco Irriflow EM Meter – Transducer (left) and Turnout Installation (right)

It is worth noting that CICL experienced problems with the electronics in the first batches of EM meters to be installed. These electrical problems appear to have been resolved by the meter vendor.

Automatic gate

The automatic gates used by CICL in canal regulators can also be installed in farm turnouts to replace Dethridge wheels. Indeed, some 126 automatic gates have now been installed in farm turnouts since 2003. The advantage of Rubicon Flumegates in turnouts include: accurate metering, remote operation, stable flow rates onto the farm, low head loss, and full integration into the existing Coleambally SCADA communications network.

CICL experienced some problems with drifting level sensors in the automatic gate. The consequent degradation of measurement accuracy eroded user confidence in the gate as a metering device. In response, Rubicon developed an ultrasonic level sensor which was retrofitted to farm turnout gates in 2005. Subsequently, the automatic gate has proven to be a robust and stable metering device.

SUMMARY AND CONCLUSION

This paper provides an overview of the Coleambally Irrigation Area modernization project. Development of the project commenced in 2000 with the objective of improving channel conveyance efficiency, reducing operating costs and enhancing water supply services. To date, some AU$16 million has been expended on capital works for the modernization project. Conveyance efficiency has been improved from 75% before the project, to 89% in the 05/06 irrigation season saving approximately 60 billion litres of water per year. The cost of the project has been recovered by selling water savings to district irrigators and to government for use as an environmental flow. This paper focuses on two key areas of the modernization project: automation of canal operations and accurate flow measurement in farm turnouts.

Building on the success of the modernization project to date, Stage 2 of the project will commence in late 2007. Stage 2 will see the deployment of accurate meters in all farm turnouts, the installation of meters and telemetry on all groundwater bores, the construction of off-stream storage and the roll out of a program to install soil moisture sensors and telemetry in irrigation fields. It is expected that Stage 2 of the project will assist irrigators to improve the efficiency of on–farm water use complementing the gains in conveyance efficiency achieved in the canal network.

REFERENCES

Australian National Committee on Irrigation and Drainage (ANCID). 2002. Know the Flow Training Manual. Tatura.

Murray Darling Basin Commission (MDBC). 2007. River Murray System Drought Update No. 7. April. Canberra.

National Measurement Institute (NMI). 2006. Meters Intended for the Metering of Non Urban Water in Open Channels and Partially-filled Pipes, Part 1: Metrological and Technical Requirements. NMI M10B-1, Third Draft. December. Canberra.

IRRIGATION SYSTEM MODERNIZATION IN THE MIDDLE RIO GRANDE VALLEY

David Gensler[1]
Ramchand Oad[2]
Kristoph-Dietrich Kinzli[3]

ABSTRACT

The Middle Rio Grande Conservancy District (MRGCD) was officially founded in the 1920's, but it may well be the oldest operating irrigation system in North America. Prior to the arrival of European explorers, the area's Pueblo cultures were practicing flood irrigation along the banks of the Rio Grande. More elaborate irrigation practices were introduced to the Middle Rio Grande Valley by Spanish explorers in the 1600's and irrigation and water delivery practices have remained virtually unchanged for the past 300 to 400 years. Currently the MRGCD serves about 55,000 acres of irrigated land and provides additional benefits to the Middle Rio Grande (MRG) Valley by providing water for domestic, industrial, and environmental needs.

In recent years the demand for water in the Middle Rio Grande Valley has increased drastically due to explosive population growth, expanding industry, and water allocated for environmental and ecological concerns, that include two federally listed endangered species -- the silvery minnow (Hybognathus amarus), and the southwestern willow fly catcher (*Empidonax traillii extimus).* In response to the call for more efficient water use, the MRGCD embarked on a program of irrigation system modernization with SCADA incorporation. Over the past few years, the MRGCD has developed a SCADA system with the focus being to improve water use efficiency throughout the Middle Rio Grande Valley. This paper examines the five components of the system and how each component was developed and incorporated in the overall SCADA system. The SCADA system and related improvements in operational practices have reduced MRGCD river diversions from 600,000 AF/year to an average of 350,000 AF/year over the last three years.

INTRODUCTION

Middle Rio Grande Valley

The Middle Rio Grande (MRG) Valley extends 175 miles, north to south, through central New Mexico from Cochiti Reservoir to the headwaters of Elephant Butte Reservoir (Oad and Kullman, 2006). The Rio Grande passes through this valley on its journey from the high country of Colorado and northern New Mexico, to the Gulf of Mexico (Figure 1). Throughout the MRG valley, the Rio Grande is bordered by bosque, or riverside forest. Adjacent to the bosque, but within the narrow historic floodplain of the river, there is widespread irrigated agriculture. The City of

[1]Hydrologist, Middle Rio Grande Conservancy District, Albuquerque, NM; dgensler@mrgcd.com
[2]Professor, Department of Civil and Environmental Engineering Colorado State University, Fort Collins, CO; oad@engr.colostate.edu
[3]Graduate Research Assistant, Department of Civil and Environmental Engineering Colorado State University Colorado State University, Fort Collins, CO; kkinzli@engr.colostate.edu

Albuquerque and several smaller communities are located in and adjacent to the MRG Valley. Although the valley receives less than 10 inches of rainfall annually, the MRG supports both productive agriculture, and a rich and diverse ecosystem of fish and wildlife (Oad and Kullman, 2006).

Figure 1. The Middle Rio Grande Valley

Water supply available for use in the MRG Valley includes: native flow of the Rio Grande and its tributaries, allocated according to the Rio Grande Compact of 1938; San Juan-Chama (SJC) project water, obtained via a trans-mountain diversion from the Colorado River system; and groundwater

(Rio Grande Compact Commission, 1997). Water is fully appropriated in the MRG Valley and its utilization is limited by the Rio Grande Compact. The Compact sets forth a schedule of deliveries of native Rio Grande water from Colorado to New Mexico and from New Mexico to Texas (Rio Grande Compact Commission, 1997).

In addition to agricultural and domestic consumers, there is major water use in the MRG associated with riparian vegetation. Open water evaporation from reservoirs and the river is also substantial. Across the American West, irrigated agriculture uses roughly 80 to 90% of available surface water. In the MRG use is more or less equally divided between agriculture, domestic use, and riparian consumption. Superimposed on these demands are river flow targets associated with two federally-listed endangered species: the silvery minnow (Hybognathus amarus) and the southwestern willow fly catcher (*Empidonax traillii extimus)* (USFWS, 2003).

Middle Rio Grande Conservancy District (MRGCD)

The MRGCD may well be the oldest operating irrigation system in North America. Irrigation practices introduced by Spanish explorers in the 1600's supplanted pre-historic flood irrigation by the area's Pueblo Indians. At the time of Albuquerque's founding in 1706, the ditches which now constitute the MRGCD were in existence, operating as independent Acequia associations. Acequias consisted of small farmer groups that maintained individual irrigation canals. Irrigated agriculture in the MRG valley reached its greatest extent in the 1880’s, but thereafter underwent a significant decline.

Surprisingly, this decline was caused by an overabundance of water. By the early 1920’s inadequate drainage, periodic flooding, and climatic variables had resulted in water logged soils throughout the MRG valley. Swamps, seeps, and salinization of agricultural lands were the result. In 1925, the State of New Mexico passed the Conservancy Act, which authorized creation of the MRGCD, which was accomplished by combining 79 independent Acequia associations into a single entity (Figure 2). Irrigated lands of six Indian Pueblos were also incorporated within the service area of the MRGCD. Physical construction began in 1928, and was completed by 1932 with river headings of Acequias becoming laterals, consolidated by building 6 diversion works and a series of main canals. A high mountain storage reservoir, El Vado, was completed in 1935.

In the mid 1990's the MRGCD encountered the same pressures for change currently being experienced by irrigated agriculture throughout the world. An ever expanding urban population began looking toward agriculture as a source for water and the endangered species act placed constraints on water use. Information on climate variability and groundwater resources produced a realization that water resources were less plentiful in the region than was previously believed. In order to proactively address water shortage and agricultural water delivery, the MRGCD embarked on a comprehensive program of canal modernization and SCADA incorporation.

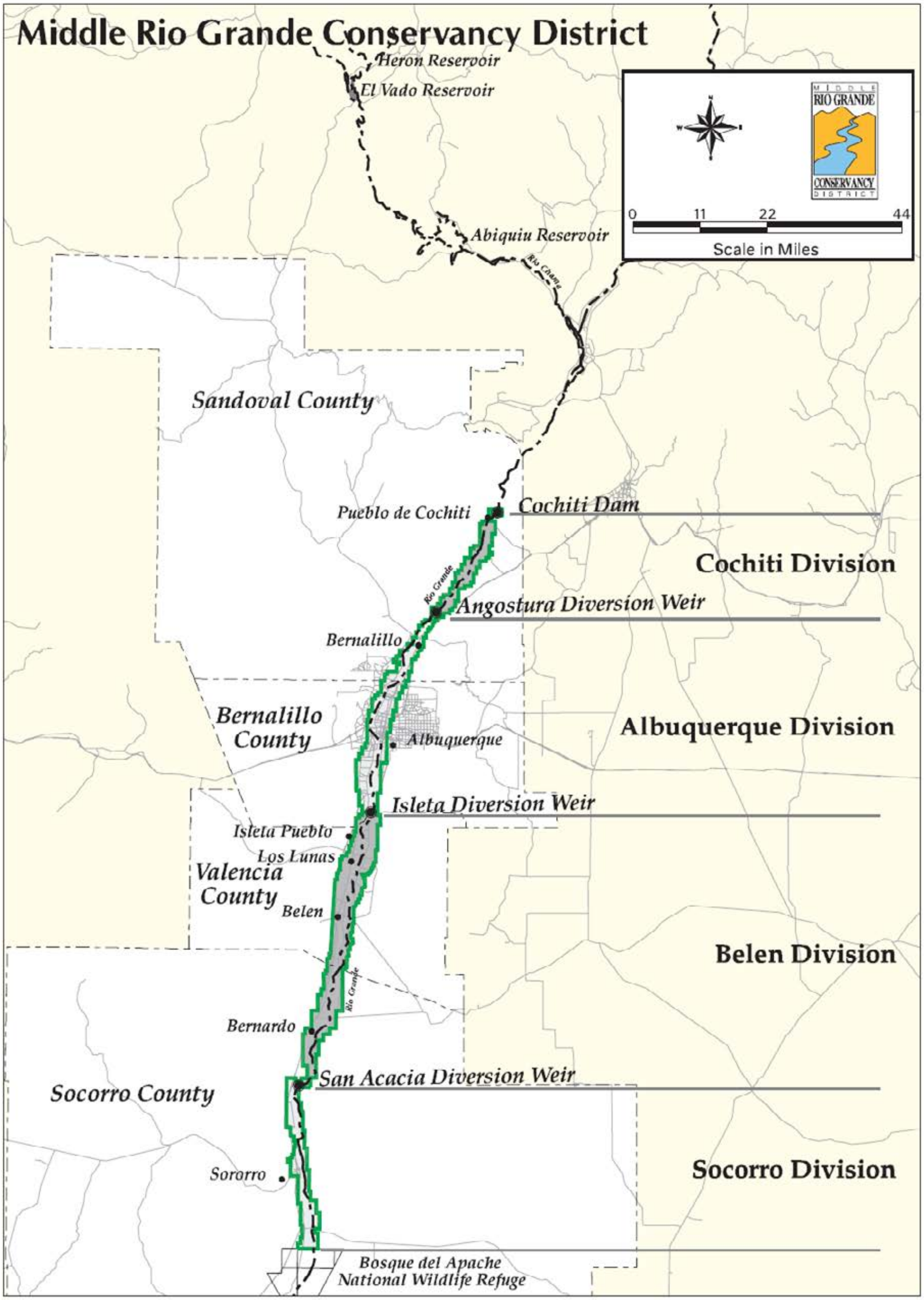


Figure 2. The Middle Rio Grande Conservancy District

MRGCD SCADA DEVELOPMET AND USE

The MRGCD program of measurement and automation was built entirely in-house using inexpensive components due to budget constraints. The components used in the system are a combination of traditional agricultural SCADA technology and adaptations of technology from other sectors of industry, most notably, the steel manufacturing industry. This combination and integration of technology makes the MRGCD SCADA setup unique. The MRGCD SCADA system can be broken into the following components:

- Flow Measurement Structures
- Automated Control Structures
- Instrumentation
- Telemetry
- Software

Water Measurement

Water measurement is the single most important component of the MRGCD's SCADA experience, since all operational decisions require sound knowledge of available water supplies and the demand throughout the system. When the MRGCD was initially constructed, considerable thought to water measurement was given. Over the years, gauging stations equipped with measurement instrumentation gradually deteriorated and quality of flow records declined.

In 1996, crisis struck the MRGCD in the form of drought, endangered species flow requirements, and development of municipal water supplies. At the time, the MRGCD was operating only 15 gauges on 1200 miles of canals. The following year, MRGCD officially embarked upon its modernization program. The construction of new flow gauges was the first step in this program. New gauges were constructed at key points in the canal system, notably at diversion structures and at return flow points. The acquisition of data from these locations led to determining where additional gauges would be most useful.

Along with the increase in numbers of gauging stations, efforts were made to improve the quality of measurement. Open channel gauging sites with no control structures gave way to site specific measuring structures. A variety of flow measurement structures were built in the MRGCD and include sharp crested weirs, broad crested weirs, adjustable weirs and Parshall flumes. Soon after beginning the modernization program, the Bureau of Reclamation WINFLUME software became available. Since that time new gauges are constructed with broad-crested weirs using WINFLUME for design and calibration (Figure 3). Currently, MRGCD is operating 75 gauges.

Figure 3. Broad Crested Weir Gauging Station with Radio Telemetry

<u>Automated Control Structures</u>

With the advent of better data collection, it became apparent to the MRGCD that automated control was necessary. Data from gauges revealed that many operational problems occurred because canal operators could not be physically present at all times. Automation followed shortly thereafter with an experimental effort at a wasteway that had been fitted with an automated Langemann gate for water measurement, and was therefore a practical starting point. The MRGCD built the electronic controller and created the control software for this first automated gate, borrowing heavily from Bureau of Reclamation experience in Utah. Success with the first automated structure led to installation of over 40 additional automated structures. After the first in-house development of automation, it was found practical to use existing commercial control products, although the experience gained from initial development has proved invaluable.

Most of MRGCD's recent automation efforts have involved the installation of Langemann overshot gates (Aqua Systems, 2006). The majority of these can be easily retrofitted to existing structures, though some involve the construction of new check or heading structures. The Langemann Gate has the capability to maintain a constant upstream water level as a check structure or it can provide a constant flow rate to downstream users (Figure 4). The Langemann gate is equipped with solar panels to power both gate operation and telemetry units. The gates employ integrated electronic controllers built around IC Tech radio terminal units (RTU's) and Aqua Systems 2000 software. Langemann gates in the MRGCD are used as checks, turnouts, spillways, and diversion structures.

Figure 4. Langemann Gate

Some existing radial gates have also been automated. Conversion involves selection of a gearbox, motor, and controller. Some fabrication is involved to adapt the drive unit to the existing gate hoist shaft, but this is all done in-house by MRGCD shop personnel. Early conversion attempts used an AMI controller supplied by Aqua Systems 2000, but recently the MRGCD has used the IC Tech RTU (Figure 5), which can be programmed to calculate flow through automated radial gates. Though not as accurate as overshot gates, this is useful for setting target bypass flows at diversion structures for endangered species flow requirements.

Instrumentation

Flow measurement and automated control must include some level of instrumentation. In the 1930's, a float in a stilling well driving a pen across a revolving strip of paper was adequate. In fact, at the beginning of modernization efforts, the MRGCD was still using 15 Stevens A-71 stage recorders. Diversions into the canal system were only known after the strip charts were collected and reduced at the end of the irrigation season.

Modernization meant a device was needed to generate an electrical or electronic output that could be digitally stored or transmitted. Initially, shaft encoders were used for this purpose, providing input for electronic data loggers. Experimentation with submersible pressure sensors soon followed, and these have been adopted, although a number of shaft encoders are still in use. Recently, sonar sensors have been used satisfactorily at a number of sites. The MRGCD has learned that different situations call for specific sensor types and sensors are selected for applications where they are most appropriate.

Telemetry

Data from electronic data-loggers was initially downloaded manually and proved to be only a minimal improvement over strip chart recording, though processing was much faster. To address data downloading concerns telemetry was adopted to bring the recorded data back to MRGCD headquarters at regular intervals (Figure 3). MRGCD's initial exposure to telemetry was through the addition of GOES satellite transmitters to existing electronic data loggers. This method worked, but presented limitations. Data could only be transmitted periodically, and at regularly scheduled intervals. Of greater consequence was that the GOES system, at least as used by MRGCD, was a one-way link. Data could be received from gauging stations, but not sent back to them. As experiments with automation progressed, it was clear that reliable 2-way communication would be a necessity.

To address the rising cost of phone service, experiments with FM radio telemetry were conducted. These began as a way to bring multiple stream gage sites to a central data logger, which would then be relayed via GOES to MRGCD. First attempts with FM radio were not encouraging; however a successful system was eventually developed. As this use of FM radio telemetry (licensed 450 mHz) expanded, and knowledge of radio telemetry grew, it was soon realized that data could be directly transmitted to MRGCD headquarters without using the GOES system.

The shift to FM radio produced what is one of the more unique features of the MRGCD telemetry system. The data link proved so reliable, that there was no longer a need to store data on site, and the use of data loggers was mostly discontinued, the exception being weather stations. In effect, a single desktop computer at the MRGCD headquarters has become the data-logger for the entire stream gauge and gate system, being connected to sensors in the field through the FM radio link. Three repeater sites are used to relay data up and down the length of the valley, with transmission being up to 75 miles. Also, this has the benefit of being a 2-way link, so various setup and control parameters can be transmitted to devices along the canals.

The MRGCD telemetry network consists exclusively of IC Tech RTU’s (Figure 5). Several different types of these units are used, depending on the application. The simplest units contain only a modem and radio, and transmit collected and processed weather station data from Campbell Scientific CR10X dataloggers.

Figure 5. IC Tech Controller

The majority of the RTU's contain a modem, radio, and an input/output (I/O) board packaged into a single unit. Sensors can be connected directly to these and read remotely over the radio link. A variety of analog (4-20ma, 0-20ma, 0-5v) and digital (SDI-12, RS-485) output devices can be accommodated this way. Another type includes a programmable (RP-52 BASIC) controller in the modem/radio/(I/O) unit. This style is used for all automatic control sites and places where unusual processing of sensor outputs such as averaging values, combining values, or timed functions, are required. At the present time, the MRGCD telemetry network gathers data from 75 stream flow gages and 18 ag-met stations, and controls 50 automated gates (Figure 6).

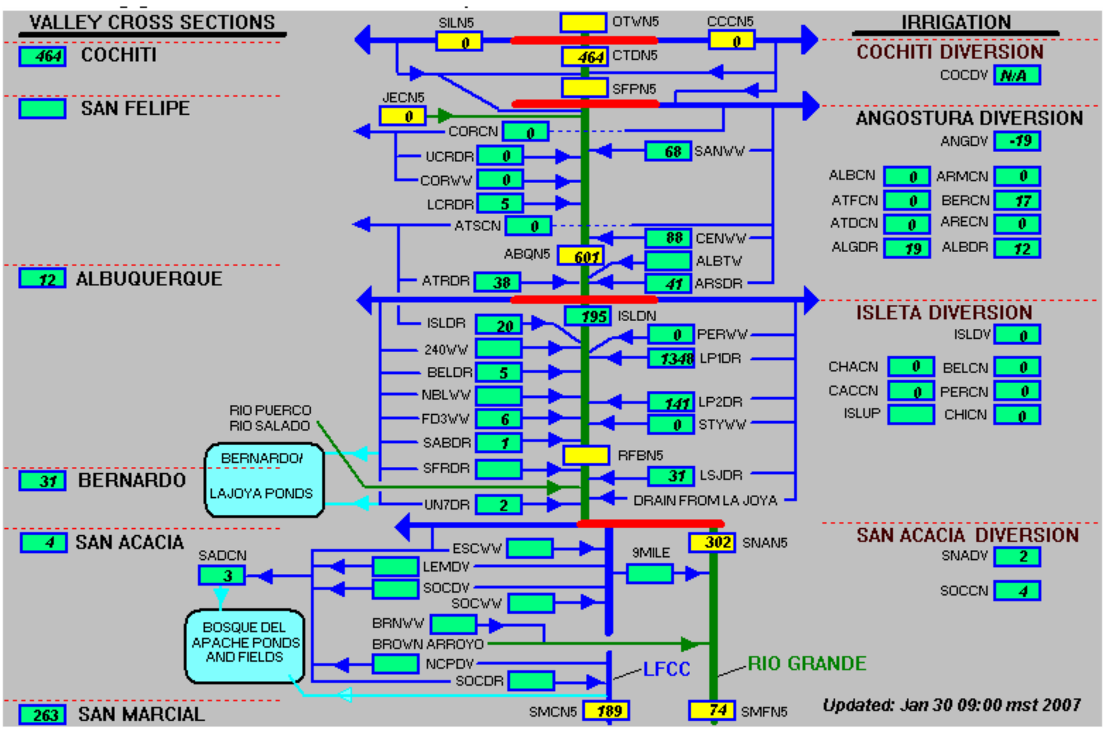


Figure 6: MRGCD Telemetry Network

Control Software

Measurement, automation, and telemetry components were developed simultaneously, but largely independent of one another. While each component functioned as expected, components did not exist as a harmonious whole, or what could truly be called a SCADA system. The missing component was software to tie all the processes together. There are a variety of commercially available software packages for such use and MRGCD experimented with several. Ultimately, the MRGCD chose to purchase the commercial software package Vsystem and to employ the vendor Vista Controls to develop new features specific to the control of a canal network. Installation and setup was done by the MRGCD.

This system, known affectionately as the Supervisory Hydro-data Acquisition and Handling System (SHAHS), gathers data from RTU's on a regular basis. With the capability to define both timed and event driven poll routines, and specify a virtually unlimited number of RTU's and MODBUS registers to collect, virtually any piece of information can be collected at any desired time. The Vsystem software can process data through a myriad of mathematical functions, and combine outputs from multiple stations. Vsystem also incorporates the ability to permanently store data in its own internal database, MS Sequel databases, or export data in other formats. Data can be displayed in a user-created graphical user interface (GUI) which MRGCD water operations personnel use to monitor water movement. The screens can also execute scripts to generate data, control parameters, control gate set points, and monitor alarm conditions for automated control structures. Finally, the GUI's can be used to control automated structures by transmitting new parameters and setpoints. Figures 7 and 8 illustrate operation, display, and use of Vsystem components.

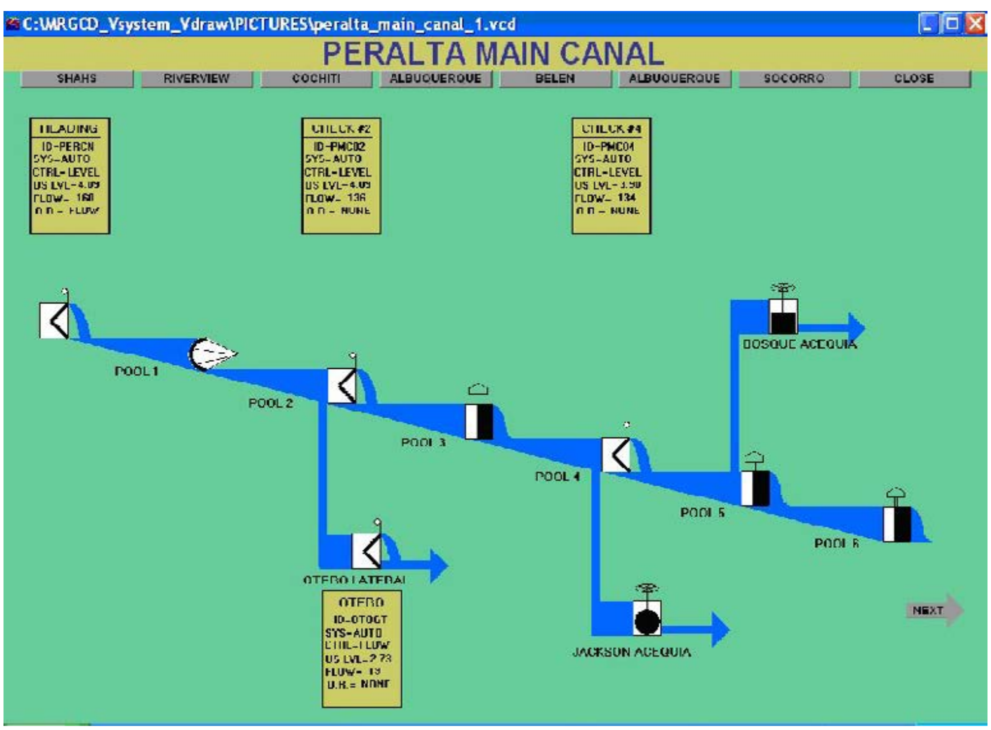


Figure 7. Vsystem Screen Displaying Check Structures and Pools on a Main Canal

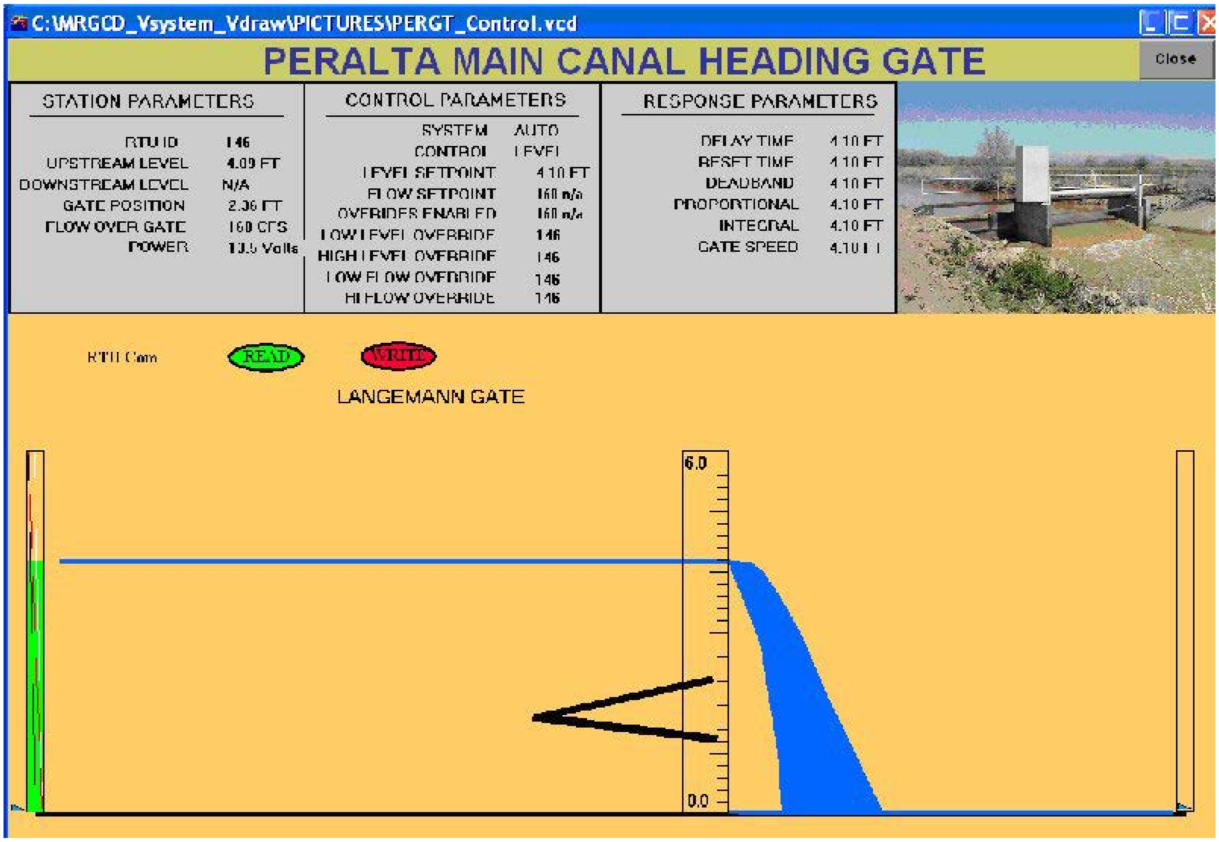


Figure 8. Vsystem Control Screen for a Langemann Gate

Decision Support System for Rotational Water Delivery

A new and very useful component is currently being incorporated into the MRGCD SCADA system. A Decision Support System (DSS) had been developed by Colorado State University to encompass irrigated agriculture in the MRG (Oad et.al, 2006). The DSS monitors soil moisture and includes a model to calculate crop water demands for lateral service areas on a real time basis. The model then develops rotational water delivery schedules to meet the crop demand. The DSS will give MRGCD operators a required irrigation delivery on a lateral level based on crop demand. This required delivery will be imported into the GUI of the MRGCD SCADA system so that actual deliveries along the canal system can be compared to required deliveries. The GUI will allow water managers to remotely change automated gate settings so that actual diversions closely represent water requirements. This will provide better water management within the MRGCD and allow for a minimized river diversion as the required and actual diversion values converge.

RESULTS AND CONCLUSIONS

The adoption of new technology has resulted in a simple, inexpensive, and reliable SCADA system. When coupled with modified operational practices, the results have been significant. A decade ago the MRGCD was diverting over 600,000 AF/year from the Rio Grande. Over the last 3 years diversions have averaged less than 350,000 AF/year (Figure 9). With a delivery obligation of 190,000 AF/yr, there is still the opportunity to further minimize river diversions. The incorporation of the previously mentioned DSS will greatly assist the MRGCD in reducing diversions to more closely represent the required crop demand in the coming years.

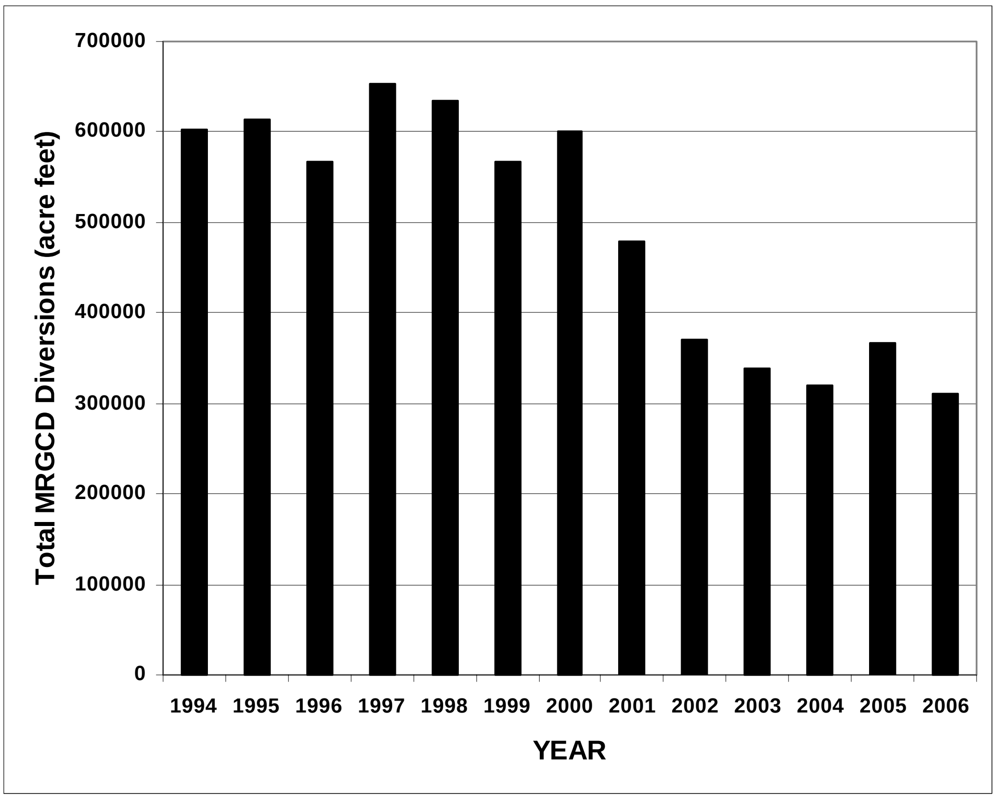


Figure 9. MRGCD River Diversions by Year

Although many irrigators miss the old days of unscheduled irrigation at the time of their choice, they have reaped a major benefit from these changes. New Mexico has experienced a decade of drought and reservoir storage has been minimal. Due to the modernization and accompanying improvement in efficiency, a much smaller volume of water is released from upstream storage reservoirs to meet a given demand. Therefore, the limited supply of stored water is stretched farther. During the recent drought the MRGCD has not had to curtail deliveries for any extended periods of time, and irrigators have continued to receive their full annual deliveries.

Additionally, New Mexico has done unusually well in meeting Rio Grande Compact delivery obligations over the last few years. This is due to many factors, but one major reason is the more efficient movement of water through the middle valley by the MRGCD. Annual carryover storage has also increased as a result of efficiency improvements. This translates to less empty storage space to fill during spring runoff. Currently, more water goes downstream during runoff mimicking the hydrograph before the advent of storage reservoirs. This is a subtle change, possibly overlooked by many, but one which may ultimately provide more good for endangered species and the general welfare of the river system than additional artificial releases for those purposes.

ACKNOWLEDGEMENTS

The authors would like to thank Subhas Shah, the MRGCD Board of Directors, the New Mexico Interstate Stream Commission, the New Mexico Office of the State Engineer, the Middle Rio Grande Endangered Species Act Collaborative Program, the United States Army Corp of Engineers, and the United States Bureau of Reclamation for the assistance and the financial support to undertake this project. Also, the exceptional support of Jim Conley at IC Tech, Gerald Robinson and Lee Allen at Aqua Systems 2000, and Cathy Laughlin and Peter Clout of Vista Control Systems is graciously recognized.

REFERENCES

Aqua Systems 2000 Inc (2006). www.aquasystems2000.com Accessed 2/28/2006

Oad, Ramchand and R. Kullman (2006). Managing Irrigated Agriculture for Better River Ecosystems—A Case study of the Middle Rio Grande. Journal of Irrigation and Drainage Engineering, Vol. 132, No. 6: 579-586. American Society of Civil Engineers, Reston, VA.

Oad, R. Garcia, L. Kinzli, K-D. Patterson, D. (2006) Decision Support Systems for Efficient Irrigated Agriculture. (2006). Sustainable Irrigation Management, Technologies and Policies. WIT Transactions on Ecology and Environment. Wessex Institute of Technology, Southampton UK.

Oad, Ramchand and K. Kinzli (2006). SCADA Employed in Middle Rio Grande Valley to Help Deliver Water Efficiently. Colorado Water – Newsletter of the Water Center of Colorado State University. April 2006,

Rio Grande Compact Commision. (1997). Report of the Rio Grande Compact Commission.

United States Department of Agriculture (USDA). 1967. Irrigation Water Requirements. Technical Release No. 21.

U.S. Department of Interior (2003). Water 2025: Preventing Crisis and Conflict in the West. U.S Bureau of Reclamation.

RELATIONSHIP OF OPERATION STABILITY AND AUTOMATIC OPERATION CONTROL METHODS OF OPEN CANAL

Feng Xiaobo[1]
Wang Changde[2]
Guan Guanghua[3]

ABSTRACT

Water level in open canal fluctuates with the change of the discharge. The water flow from one steady state to another will take a period of time. For a certain canal, the process of the dynamic response is affected by using different automatic control methods. In order to shorten the response time and limit the fluctuating range of water level, maintain the performance of automatic control canal system stability, proper automatic canal control methods should be adopted. In this study, taking the middle route of China's South-to-North Water Diversion Project as an example, the relationship of operation stability and automatic control methods of open canal is studied by means of numerical simulation of unsteady flow in open canal with different control methods, and some useful results on the automatic canal control system of the middle route of Chinese South-to-North Water Diversion Project are obtained.

INTRODUCION

To deliver the appropriate amount of water to a user at the appropriate time, the performance of irrigation water delivery canal systems with automatic control should maintain stability. Water level in open canal fluctuates with the change of the discharge. The water flow from one steady state to another will take a period of time. For a certain canal, this process is affected by the canal operation control methods, range of discharge change and rate of it. In order to shorten the response time and limit water level fluctuating range, maintain the performance of automatic control canal system stability, proper automatic canal control methods should be adopted.

The middle route of China's South-to-North Water Diversion Project is the longest distance open canal with flat slope and very large design discharge, but lacks necessary in-line water storage. To improve the flexibility of water delivery while also maintaining the performance stability, automatic control methods should be studied and well-chosen. In this study, taking the middle route of China's South-to-North Water Diversion Project as an example, the relationship of operation stability and automatic control methods of open canal is studied by means of numerical simulation of unsteady flow in open canal with different control methods, and some useful results

[1]Lecturer; School of Water Resources and Hydropower, Wuhan University, Wuhan 430072, China; fengxb999@21cn.com
[2]Professor; School of Water Resources and Hydropower, Wuhan University; Wuhan 430072, China; cdwwh@tom.com
[3]Lecturer; School of Water Resources and Hydropower, Wuhan University; Wuhan 430072, China; GGH@whu.edu.cn

on the automatic control system of the middle route of China's South-to-North Water Diversion Project are obtained.

NUMERICAL SIMULATION OF AUTOMATIC OPERATION CONTROL CANAL

Numerical simulation model of automatically control canal is composed of control algorithm of the controller and hydraulic equations of the transient flow in canal.

One-dimensional Unsteady Non-uniform Flow in Open Canal

Equations Generally, the Saint Venant equations are used to define one-dimensional unsteady non-uniform flow in open canal. The Saint Venant equations, which consist of a continuity equation (Equation (1)) and a momentum equation (Equation (2)), can be expressed as (Xu Zhengfan, 1986):

$$B\frac{\partial z}{\partial t}+\frac{\partial Q}{\partial s}=q \tag{1}$$

$$\frac{\partial Q}{\partial t}+2v\frac{\partial Q}{\partial s}+(gA-Bv^2)\frac{\partial z}{\partial s}=Bv^2(i+M)-g\frac{Q^2}{A^2C^2R} \tag{2}$$

Where B is the width of canal water surface(m); z is the water surface elevation(m); t is the time(s); Q is the discharge(m^3/s); C is the Chezy coefficient; s is the distance along the canal(m); q is the inflow along the canal side(m^3/s/m); g is the gravitational acceleration(m/s^2); A is the cross-sectional area(m^2); v is the flow velocity along canal axes of the canal side inflow(m/s), R is the hydraulics radius(m); i is the canal bottom slope; $M=\frac{1}{B}\cdot\frac{\partial A}{\partial s}\big|_h$.

Solution of The Saint Venant Equations The Preissmann implicit scheme is widely adopted as the numerical solution method of Saint Venant equations for its fine characteristics such as high accuracy and unconditional convergence. In this method, the s-t plane of solution domain is divided into a regular rectangular net, then difference quotients are used to approach the partial derivatives of dependent variables (Z and Q). The following discrete equations on each grid can be deduced:

$$a_{1i}Z_i^{j+1}-c_{1i}Q_i^{j+1}+a_{1i}Z_{i+1}^{j+1}+c_{1i}Q_{i+1}^{j+1}=e_{1i} \tag{3}$$

$$a_{2i}Z_i^{j+1}+c_{2i}Q_i^{j+1}-a_{2i}Z_{i+1}^{j+1}+d_{2i}Q_{i+1}^{j+1}=e_{2i} \tag{4}$$

Where $a_{1i} = 1$; $c_{1i} = 2\theta \frac{\Delta t}{\Delta s_i} \frac{1}{B_M}$; $e_{1i} = Z_i^j + Z_{i+1}^j + \frac{1-\theta}{\theta} c_{1i} (Q_i^j - Q_{i+1}^j)$;

$a_{2i} = 2\theta \frac{\Delta t}{\Delta s_i} (V_M{}^2 B_M - gA_M)$; $c_{2i} = 1 - 4\theta \frac{\Delta t}{\Delta s_i} V_M$; $d_{2i} = 1 + 4\theta \frac{\Delta t}{\Delta s_i} V_M$;

$$e_{2i} = \frac{1-\theta}{\theta} a_{2i} (Z_{i+1}^j - Z_i^j) + [1 - 4(1-\theta) \frac{\Delta t}{\Delta s_i} V_M] Q_{i+1}^j + [1 + 4(1-\theta) \frac{\Delta t}{\Delta s_i} V_M] Q_i^j$$

$$+ 2\Delta t V_M{}^2 \frac{A_{i+1}(Z_M) - A_i(Z_M)}{\Delta s_i} - 2\Delta t \frac{gn^2 Q_M{}^2 P_M{}^{4/3}}{A_M{}^{7/3}}$$ 。

Where the hydraulics parameter of the center difference $\varphi_M = \theta(\frac{\varphi_i^{j+1} + \varphi_{i+1}^{j+1}}{2}) + (1-\theta)\frac{\varphi_i^j + \varphi_{i+1}^j}{2}$,

φ refers to the water surface elevation Z, the discharge Q, the velocity V, the water surface width B, the cross-sectional area A or the wetted perimeter P; the subscript i is the space layer serial number, the superscript j is the time layer serial number, θ is the weight factor (usually choose from 0.7~0.75).

Combining all the equations, a set of large-scale sparse nonlinear equations which can be solved by double elimination methods (recursion methods) are obtained.

Control Algorithm

A control algorithm is a prescribed set of well defined rules or processes for the solution of a problem in a finite number of steps. The algorithm is designed to process the input information from the sensors, perform the comparator function, and calculate the proper output to the actuator. The input is quantities of parameters those are observed, measured, or predicted such as water levels; the output is a control action such as gate movement. Control algorithm can be translated to a computer program and executed by computer. In this study, control effect is compared between two different control algorithms. One is the Proportional+ Proportional plus Reset control (P+PR), another is Linear Quadratic Regulator control (LQR).

P+PR Control The incremental P+PR control algorithm can be described as follow:

$$\Delta G(k) = K_P[e(k) - e(k-1)] + K_I e(k) = K_P \Delta e(k) + K_I e(k) \quad (5)$$

Where ΔG is the output of feed-back control; K_p is the proportional coefficient; K_I is the integral coefficient; e is the difference of water levels; Δe is described by $\Delta e(k) = e(k) - e(k-1)$;

k is the sampling time.

Block diagram of P+PR control is shown in Figure 1.

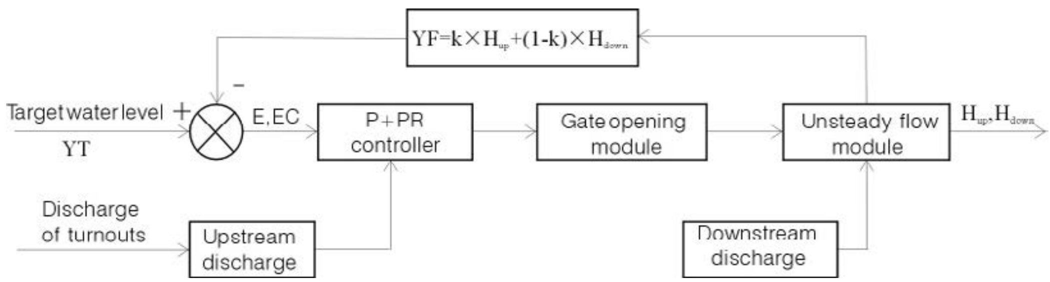


Figure 1. Block Diagram of P+PR

The target level YT in Figure 1 can be upstream water level, downstream water level or weighted value of both. When the weighting factor K is equal to 0， the operation method is upstream control. When K equal to 0.5, it is constant volume control.

<u>LQR Control</u> LQR control is based on state-space theory. In this study, the Saint Venant continuity equation and momentum equation is first discretized by the Preissmann implicit scheme, and equations that have been discretized are expanded in Taylor series at each equilibrium point. Taking only the linear terms, omitting the higher terms, the linear discrete-time state-space model can be deduced as follow (Zhao Wenfeng, 2002):

$$\delta x(k+1) = \Phi \delta x(k) + \Gamma \delta u(k) + \Psi \delta q(k) \tag{6}$$

where $\Phi = (A_L)^{-1} \times A_R$ is a $l \times l$ feedback matrix; $\Gamma = (A_L)^{-1} \times B$ is a $l \times m$ control matrix; $\Psi = (A_L)^{-1} \times C$ is a $l \times p$ disturbance matrix; $\delta x(k)$ is a $l \times l$ state vector; $\delta u(k)$ is a $m \times l$ control vector; $\delta q(k)$ is a $p \times l$ disturbance vector; l is the number of state variable; m is the number of control variable (gate number); k is the sampling number; p is the number of turnouts. The value of matrix Φ, Γ, Ψ is obtained by the operation state of the canal system.

Define output equations as $\delta y(k) = H\delta x(k)$, where H is the output matrix. Then the output (i.e., upstream and downstream water levels, discharges of the canal) can be obtained from the state vector δx.

The water level and discharge can be used as state vectors, gate position and discharge of turnouts is used as boundary conditions, then state-space model of the canal can describe the whole spatio-temporal hydraulic response of the operation of canal. Then, the change of the canal water levels can be translated into the transfer of state variables of the state-space model. LQR belongs to the optimization techniques which have been applied to control problems in an attempt to simplify the tuning process. In a linear response model, the controller can be tuned by minimizing a quadratic performance indicator or objective function. LQR can be used to determine the appropriate values for the non-zero constant gain matrices. In LQR theory, the gain matrix is chosen so that the value of the objective function is minimized. The objective function is a performance index of the controller and is a quadratic function of the state vector and the control actions.

Numerical Simulation of Multi-pool Canal System

From the analysis of gate operation technique, it is known that the response time is shortest if technique of synchronous gate operation is used in multi-pool canal (Bureau of Reclamation, 1991). So the technique of synchronous gate operation is used to realize computer centralized control in multi-pool in this study.

In computer centralized controlled multi-pool canal system, the water level sensor converts parameters such as upstream and downstream water level of each pool to the control system, immediately the gate sensor provides the gate position to the control system. The data form sensor will be classified, stored and manipulated by centralized control system. When the water delivery is changed, the centralized control system will adjust the positions of check gates to ensure the anticipative discharge using the technique of synchronous gate operation after computing the input parameters from the sensors. In the process of control, the system collects the input parameters and revises the output parameters frequently. The block of mathematical simulation of a multi-pool canal system is shown in Figure 2.

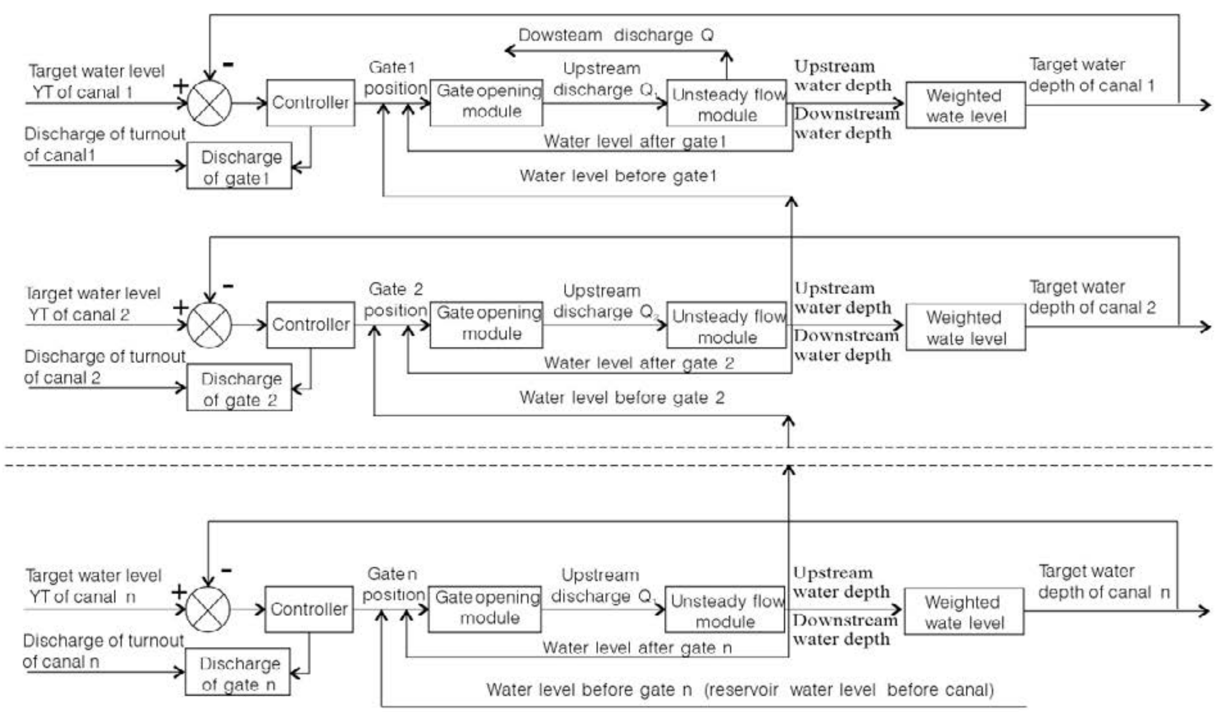


Figure 2. Block of Numerical Simulation of Multi-pool Canal System

ANALYSIS OF OPERATION STABILITY AND AUTOMATIC CONTROL METHODS ON TEST CANAL

Test Canal

The discharge and the range of discharge change at the beginning part of middle route of China's South-to-North Water diversion Project is the largest. The canal of this part is chosen as test canal to simulate the hydraulic response of the canal in several control methods. The characteristics of the test canal are: bottom width is 40m, side slopes is 3, Manning *n* is 0.015, bottom slope is 0.00004, design flow is 600m^3/s, giving a design water depth of 7.47m. The number of pools in test canal is three.

Relationship of Stability and Operation Methods

A canal's dynamic response is mostly dependent upon the method of pool operation. The method of operation is based upon the location of the canal pool water surface pivot point. There are four operation methods. Which are constant downstream depth, constant upstream depth, constant volume and controlled volume (Pierre. O. M., 1998).

In the constant upstream depth method of operation, the water depth at the upstream end of each canal pool remains relatively constant. The constant depth method is sometimes called "level bank" operation, because canal banks must be horizontal to accommodate the zero-flow profile. For cost of construction of a level bank canal is huge, this method is rarely adopted.

In the constant downstream depth method of operation, a constant downstream depth is maintained by pivoting the water surface at the downstream end of the canal pool as shown on Figure 3. This method is used in most canal systems. The primary reason why this method is so prevalent is that a canal can be sized to convey the maximum steady flow. Steady state water depths should never exceed the normal depth for the design flow rate. The canal prism size and freeboard can be minimized, thus reducing construction costs.

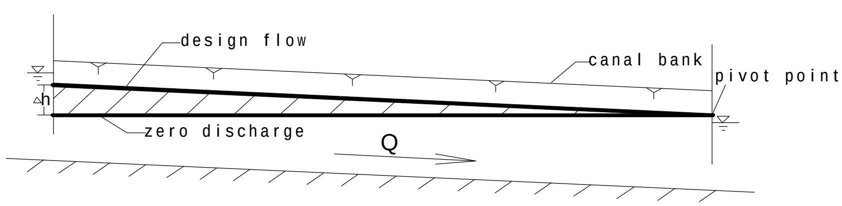


Figure 3. Constant Downstream Depth Method of Operation

The constant volume method of operation is based upon maintaining a relatively constant water volume in each canal pool at all times. The water surface will pivot about a point near midpool as the flow changes from one steady state to another as shown on Figure 4. Additional canal bank and lining is required at the downstream end of each pool, as compared to a conventional canal bank. However, the additional height required to accommodate the zero-flow water surface is only about one-half that required for level bank operation.

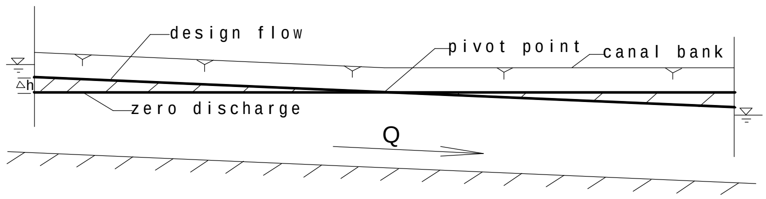
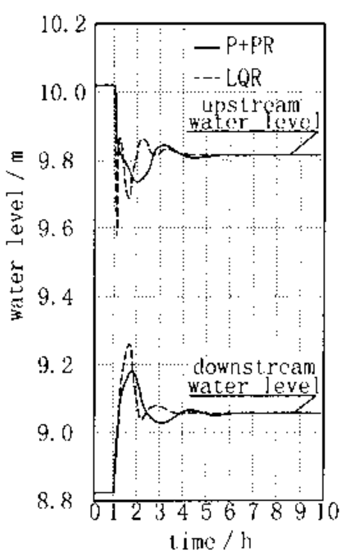


Figure 4. Constant Volume Method of Operation

The controlled volume method of operation is operated by managing the water volume contained in one or more canal pools. Volume can be changed to satisfy operational criteria by allowing the pivot point to move within each pool. This method required using the supervisory control method and possible need for greater freeboard or a large canal prism cross section in order to obtain a big volume.

In large-scale water transfer projects, the constant downstream depth and constant volume are often used (Wu Zeyu, 2005). Thus, this study compares the two methods only. In this case, the length of each pool is 30km. Initially, the canal flow is decreased from 600m^3/s to 480 m^3/s at 1 hours. The simulation results of pool 2 (middle pool) is shown in Figure 5, Figure 6 and table 1(using P+PR controller).



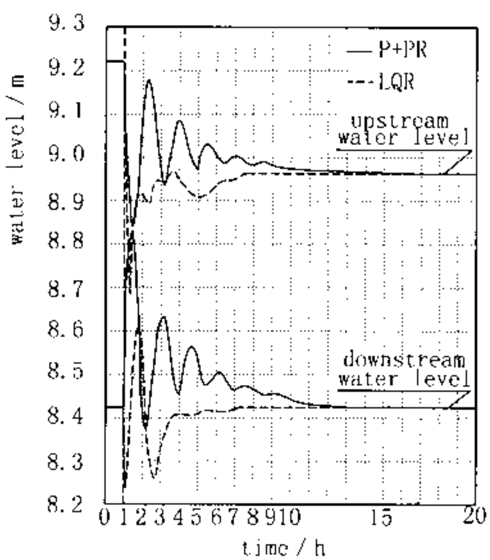


Figure 5. Constant Downstream Depth Figure 6. Constant Volume

Table 1. Hydraulic Response of the Canal 2 in Different Operation Methods

Operation methods	Position of water level	The largest variation range of water level	The most rapid drawdown	Hydraulic response time
Constant volume	Water level at upstream end of pool 2	0.281m	0.28m/h	5.6h
	Water level at downstream end of pool 2	0.356m	0.152m/h	6.2h
Control downstream depth	Water level at upstream end of pool 2	0.382m	0.787m/h	15.1h
	Water level at downstream end of pool 2	0.451m	0.338m/h	13.9h

The results show that the constant volume method of operation is better than constant downstream depth method in hydraulic response not only with P+PR controller, but also with LQR controller. The difference between constant volume and constant downstream depth is the position of pivot point (water level control point), it is shown as Figure 3 and Figure 4. For the reason that the pivot point is in the middle of pool, the time that the upstream and downstream wave comes to the control point with constant volume is shorter than with control downstream depth. Therefore, the hydraulic response with the constant volume is better than control downstream depth.

Relationship of Stability and Control Methods

Controller In this study, two typical controllers is compared. One is the P+PR controller of model basing on traditional control theory. Another is the LQR controller of a model basing on modern control theory. The result is shown in Figure 5 and Figure 6.

The result show that the two controllers basing on different control theory can both be used to the automatic control of canals, but the two kinds of controllers is each from different characteristics. The response time of LQR is shorter than P+PR, but the variation range of water level of LQR is bigger than P+PR. Compared with P+PR control model, the LQR control model in this study is more complex and can’t to deal with the case of big flow change for the reason that the equations are disposed at each equilibrium point linearity. The P+PR control model in this study is credible and can be used to most case.

Flow Change Rate and Pool Length Drawdown (drawdown is the rate of depth reduction at any point in the canal) is influenced not only by methods of operation, but also by the flow change rate and pool length. In this study, three different flow change rate (canal flow is decreased from 600m^3/s to 480 m^3/s at 1 hour, from 1 hour to 2 hour, and from 1 hour to 3 hour) and three different lengths of pool(20km, 30km and 40km) is simulated. The result is shown in Figure 7 and Figure 8.

Form the result of simulation, it is concluded that the flow change rate and pool length has a large impact on drawdown. The drawdown is increased along with the increase of flow change rate and pool length. Influence on drawdown by flow change rate is more notable than pool length. The pool length should be confirmed by the simulation of unsteady non-uniform flow in open canal with certain operation control method, but shouldn't be confirmed by the calculation of uniform open canal flow.

Flow change rate has little impact on hydraulic response time using the same control controller in a certain canal. The hydraulic response time is not same on different pool length. The greater the pool length, the longer the response time. The rate of response time increases much slower than the rate of which the pool length increases.

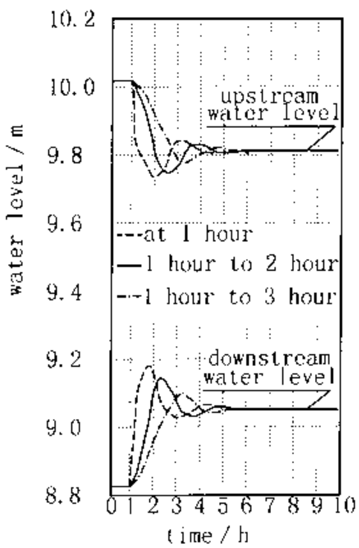


Figure 7. Control with Different Flow Change Rate

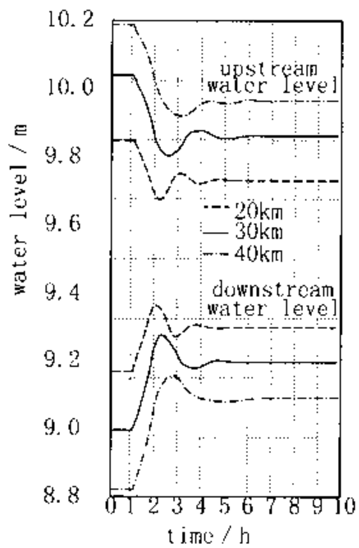


Figure 8. Control with Different Pool Lengths

CONCLUSIONS

In this study, the relationship of operation stability and automatic control methods of open canal is studied by means of numerical simulation of unsteady flow in open canal with different control methods. Form the simulation, the following conclusions can be obtained.

Control model basing on modern control theory and traditional control theory can both be used to the automatic control of canal, but each controller has its own characteristics from others. So chosen of operation control method is very important for a certain canal.

The hydraulic response of the constant volume method of operation is better than constant downstream depth in a certain centralized control canal. So constant volume method of operation is prior chosen on the conditions that the method can be used.

The flow change rate and pool length has a large impact on drawdown. The drawdown is increased along with the increase of flow change rate and pool length. Influence on drawdown by flow change rate is more notable than pool length. Thus, in order to reach an acceptable drawdown rates, a appropriate flow change rate should be chosen instead of shortening the pool length. From the simulation, the pool length of more than 30km can be able to satisfy the acceptable drawdown rates of 0.2m/h of the canal of middle route of China’s South-to-North Water Diversion Project when proper flow change rate is chosen.

REFERENCES

Bureau of Reclamation, US Department of the Interior, (1991). “Canal Systems Automation Manual”, Denver, Colo.

Pierre. O. M., David C. R., Jan S. (1998). “Classification of Canal Control Algorithms”, Journal of Irrigation and drainage engineering, (1), 2-5.

Wu Zeyu, Zhou bin, (2005). “Calculation of control model of the middle route of China’s South-to-North Water Transfer project”, (5), 1-2

Xu Zhengfan, (1986). “Hydraulics”, Higher education press, Beijing. 255-366.

Zhao Wenfeng (2002). “Design and simulation of control system”, xidian University, xi’an.

RESPONSIVE STRATEGIES OF AGRICULTURAL WATER SECTOR IN TAIWAN

Chang-Chi Cheng[1]
Chun-E Kan[2]
Kuang-Ming Chuang[3]
Ming-Young Jan[4]

ABSTRACT

In addition to increasingly frequent water shortage problems, agricultural water sector is also challenged by environmental issues. The objective of this article is to summarize, as well as propose sustainable strategies for agricultural sector in response to current environmental challenges.

For water shortage problems, which are becoming more and more frequent worldwide including Taiwan, measures for irrigation water, such as extending irrigation periods, decreasing number of irrigation application times, or rotational irrigation, are introduced and discussed. When borrowing or transfer of water among sectors is needed in Taiwan, it is usually from agricultural irrigation water to other sectors in almost all cases. The maintenance of water right, and compensation to farmers for their income loss, are the two major issues. As for environmental changes, the impact of the accession of Taiwan to WTO (World Trade Organization) is discussed specifically in this article, and a management scheme in order to save irrigation water, which could be used for other purposes, is suggested in this article.

FOREWORD

In addition to increasingly frequent water shortage problems, the agricultural water sector is also challenged by environmental issues. In this article, “environment” doesn’t only mean natural environment, but also includes political, policy, economical, technological, and societal, etc. The objective of this article is to summarize, as well as propose, sustainable strategies for the agricultural sector in response to current environmental challenges. As a result, three issues will be discussed in this article: 1)water shortage issue, 2)water transfer issue, and 3)the accession of Taiwan to WTO (World Trade Organization) issue.

WATER RESOURCES IN TAIWAN

The average annual rainfall in Taiwan is 2,515 mm, and the total volume reaches 90.5 billion m^3,

[1] Associate Professor, Department of Industrial Engineering and Management, Ching-Yun University, #229, Chien-Hsing Road, Chung-Li, Tao-Yuan, TAIWAN, phone: 886-3-4581196 ext. 6117, fax: 886-3-4683298, e-mail: faber@cyu.edu.tw
[2] Honorary Professor, Department of Bio-Environmental Systems Engineering, National Taiwan University, Taipei, TAIWAN, phone: 886-2-27023635
[3] CEO, Chi-Seng Agricultural Water Management Research and Development Foundation, Min-Chuen E. Rd. sec. 6, lane 90, #18-3F, Taipei, TAIWAN
[4] Associate Professor, Department of Civil Engineering, I-Shou University, Kaohsiung, TAIWAN, phone: 886-7-6577711 ext. 3317, e-mail: myjan@isu.edu.tw

which is approximately 2.7 times of the world average. Although the amount of rainfall sounds plenty, the water resources management is tough as the annual allocated water per capita is only around 1/8 of the world average. In addition, due to the uneven distribution both temporally as well as spatially, the overall summer wet season accounts for 78% of rainfall (nearly 90% on the most severe southern Taiwan) as seen in Figure 1.

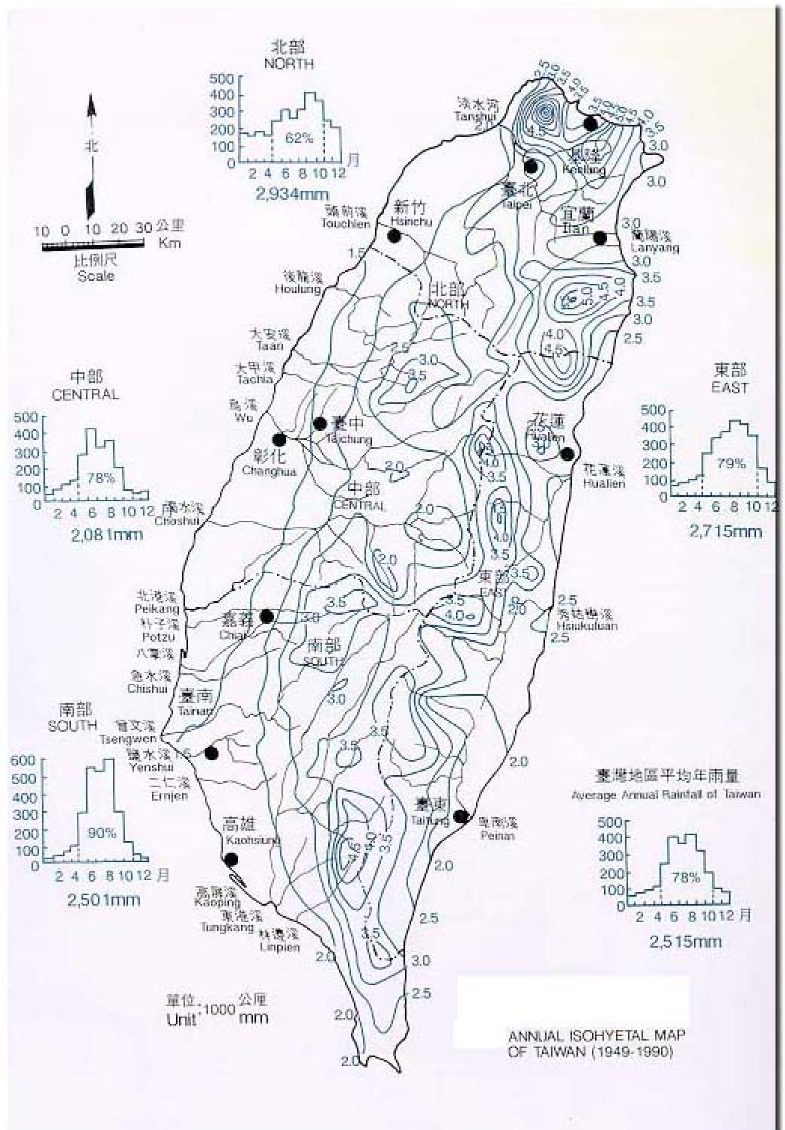


Figure 1. Annual Isohyetal Map of Taiwan

On the demand side, the statistics show that the domestic water has increased from 730 million m^3 in 1976 to 3.53 billion m^3 in 2004, and industrial water from 1.35 to 1.65 billion m^3, while agricultural water has decreased from 15.96 to 12.60 billion m^3, and has been remaining almost stable since 1996. According to WRA (Water Resources Agency), the water-resources authority, the projection of long-term demand with medium growth rate on a five-year interval targeted in year 2021 shows same trend (see Figure 2).

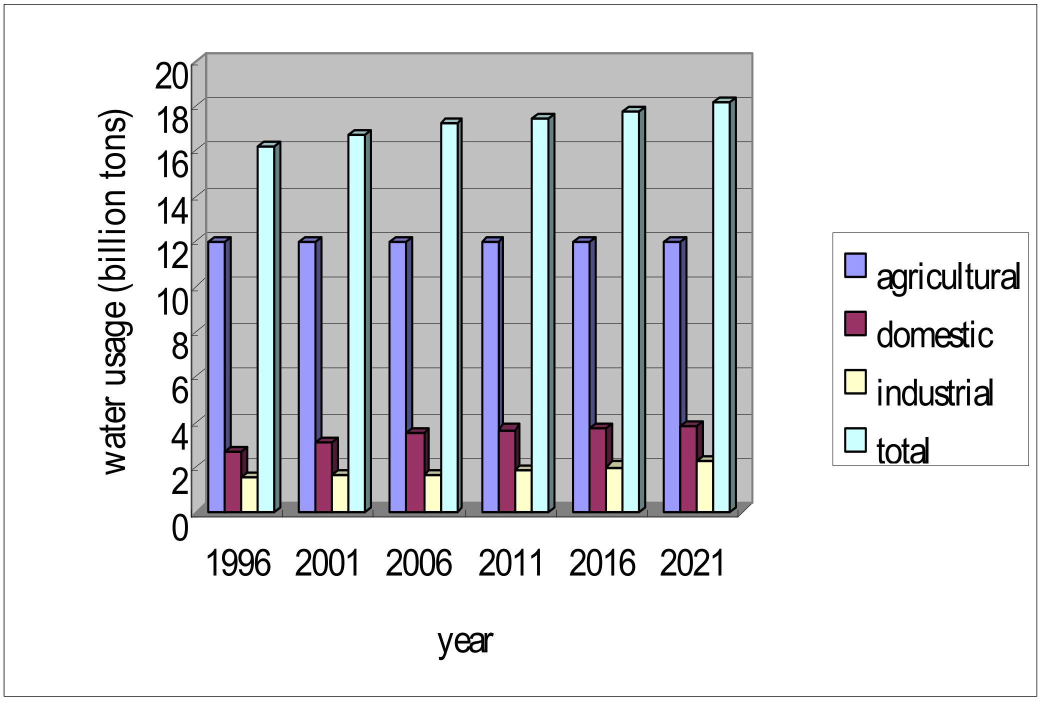


Figure 2. Trends of Water Demand for Various Sectors in Taiwan

WATER SHORTAGE ISSUE

For water shortage problems, which are becoming more and more frequent worldwide including Taiwan, each water use sector has its own priority duty to satisfy itself before seeking borrowing or transfer from other sectors. In this regard, the agricultural sector could have various measures in response to various degrees of water shortage. In this article, measures for irrigation water, such as extending irrigation periods, decreasing number of irrigation application times, or rotational irrigation, will be introduced and discussed.

General Measures for All Sectors Corresponding to Supply-Demand Analysis

From the water resources aspect, the situation of drought or water-shortage occurs when supply is not able to meet demand. The general corresponding response measures may vary according to the degree of drought conditions, i.e., the difference between the amounts of supply and demand, as shown in Figure 3.

In Figure 3, the supply and demand sides are placed on opposite sides. On the left supply side, there are three major water source categories, namely available groundwater, reservoir storage, and river flow. On the right demand side, there are four water use sectors, namely domestic, agricultural, industrial, and environmental. The starting timings to take corresponding measures are based on the difference between supply and demand conditions, and are classified into stages as follows.

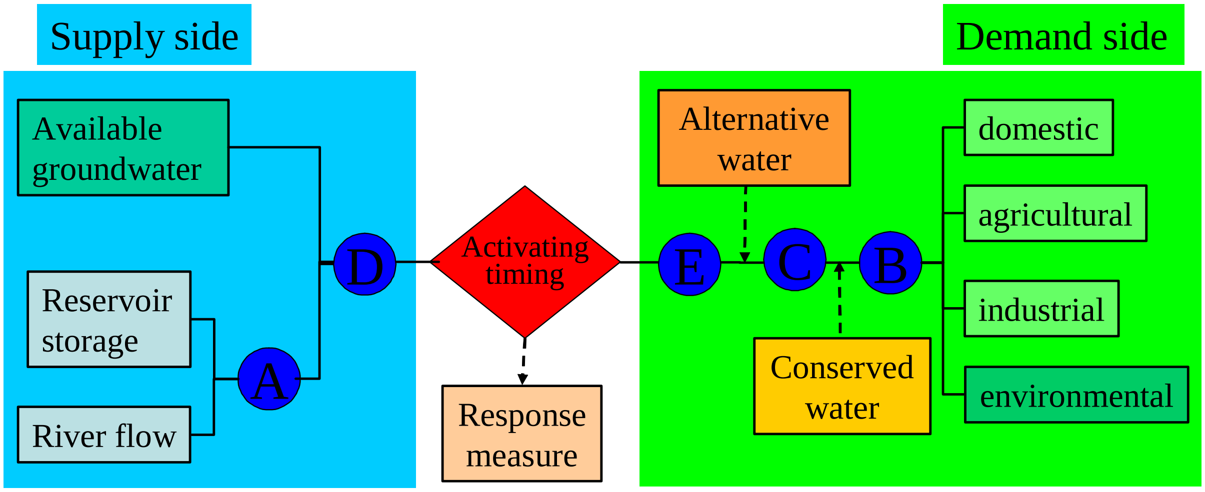


Figure 3. Supply-Demand Analysis for Water Resources Management

Stage 1 When A>B, i.e., reservoir storage and river flow are able to satisfy demand needs, then strict groundwater conservation measure is enforced.

Stage 2 When A<B, the water-saving measure is first activated. Each water-use sector has its own duty to reduce its own demand in order to keep A>C.

Stage 3 When A<C and under the tolerable safe-yield limit, groundwater is introduced for conjunctive use in order to sustain D>C.

Stage 4 When D<C, appropriate measures for different water sectors are activated. For the agricultural sector, fallow or crop change are conducted, while for the domestic and industrial sectors, alternative water sources, such as desalination water, recycled water, or reclaimed water, are introduced, in order to keep D>E.

Stage 5 When D<E, i.e., any or some of the water sectors are not capable of satisfying it or themselves, then transfer among sectors is required.

In practice, there is a similar signal system (Fig. 4, in Chinese) set by the WRA, which comprises five signal lights from blue, green, yellow, orange, to red. The activation of each signal level is based on meteorological (e.g., expected rainfall), hydrological (e.g., inflow rate, or flow level), reservoir stage, or expected demand, etc.

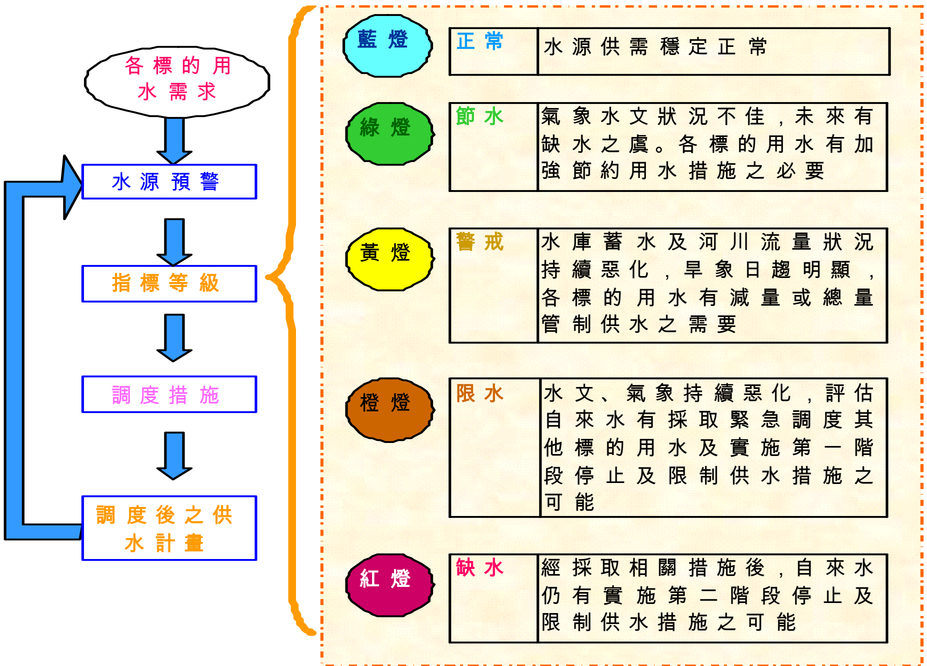


Figure 4. Signal System for Drought in Taiwan

Responsive Strategies for Agricultural Sector during Drought Seasons

Basically, for the agricultural sector there are two main strategies to be applied against drought. One is to extend the irrigation periods, which in effect, is to decrease the number of irrigation application times, and the other is to adopt rotational irrigation.

Extension of Irrigation Periods Although the irrigation periods (as well as the number of irrigation application times) are generally specified in the irrigation plans of Irrigation Associations, crops are often less vulnerable to water shortage conditions. The timing for the next application of irrigation varies with the drought-enduring ranges of crops, and is normally determined by field observation. Or, if the same amount of water is irrigated, with the number of irrigation application times being reduced, a significant amount of water loss could be saved with this practice.

This practice of extending irrigation periods must be carried out in conjunction with other measures or management schemes, such as the improvement of irrigation efficiency, or a recently promoted plan of so called “deep-water” irrigation cultivation technique. In this “deep-water” irrigation cultivation technique, the irrigation water depth is suggested to be increased from 60 mm, which is the current standard for rice cultivation in Taiwan, to 250 mm, and the estimated irrigation period could thus be lengthened up to around 20 days.

Rotational Irrigation Rotational irrigation is a scheduling process among groups of irrigation units, normally implemented to counter water-shortage problem. It is often applied at various levels of irrigation systems. In general, when the amount of irrigation water supply is above 75% and measures are to be taken, rotational irrigation is applied with main canal systems.

When irrigation water supply is between 75 – 50%, rotational irrigation is applied with lateral canal systems. When irrigation water supply is again lowered to between 50 – 25%, rotational irrigation could still be applied, but on tertiary units. When irrigation water supply is further decreased to below 25%, rotational irrigation is not suggested and extensive fallow is applied.

Two examples of Yun-Lin Irrigation Association in central Taiwan are shown below. Figure 5 is the case of rotational irrigation applied in Cho-Kan main canal system, where three irrigation areas by three laterals are involved in the rotational strategy. Figure 6 is the case in a lateral canal system where various groups are organized according to water supply to meet demand conditions.

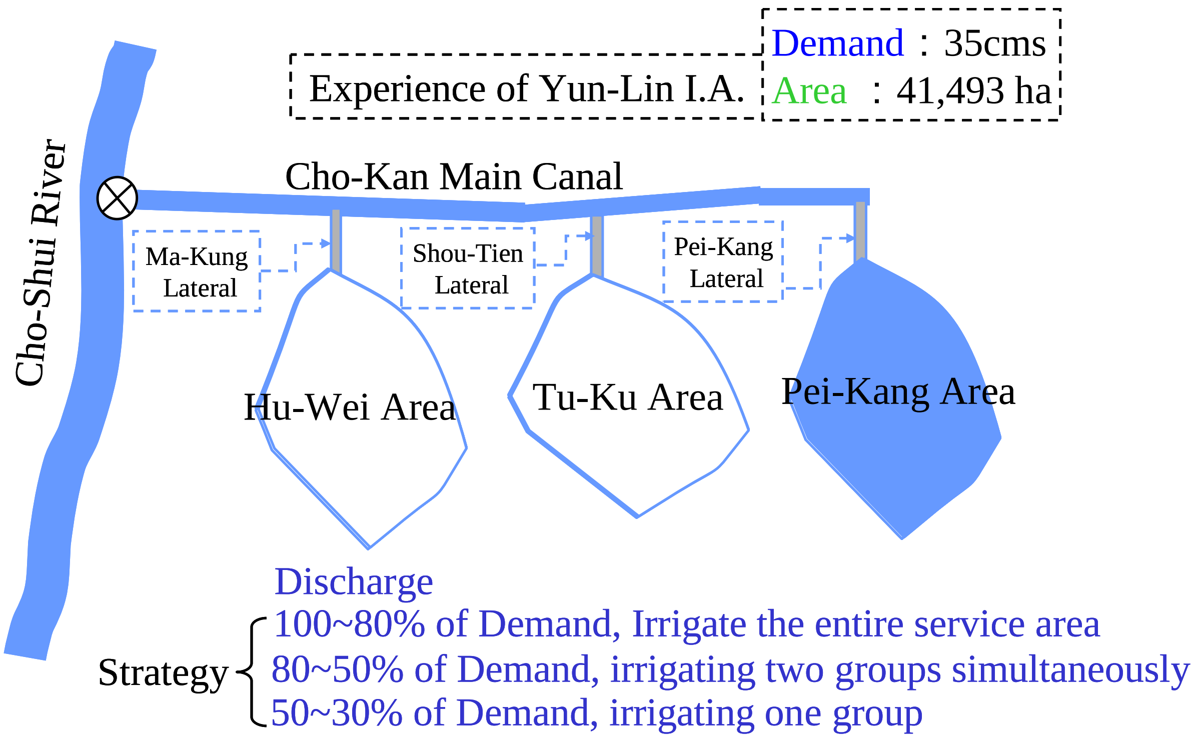


Figure 5. Example of Rotational Irrigation Applied to Main Canal System

WATER TRANSFER ISSUE

When borrowing or transfer of water among sectors is needed in Taiwan, it is usually from agricultural irrigation water to other sectors. The maintenance of water right and compensation to farmers for their income loss are the two major issues.

Most often cases of water transfer in Taiwan are from the agricultural sector to domestic. However, the industrial sector has been facing frequent water shortage problems as well, and similarly, transferring or borrowing from agricultural has become sole and important solution before specific water source intake systems are completed. As a result, it is necessary to setup a water transfer strategy among sectors in order to reach a win-win state.

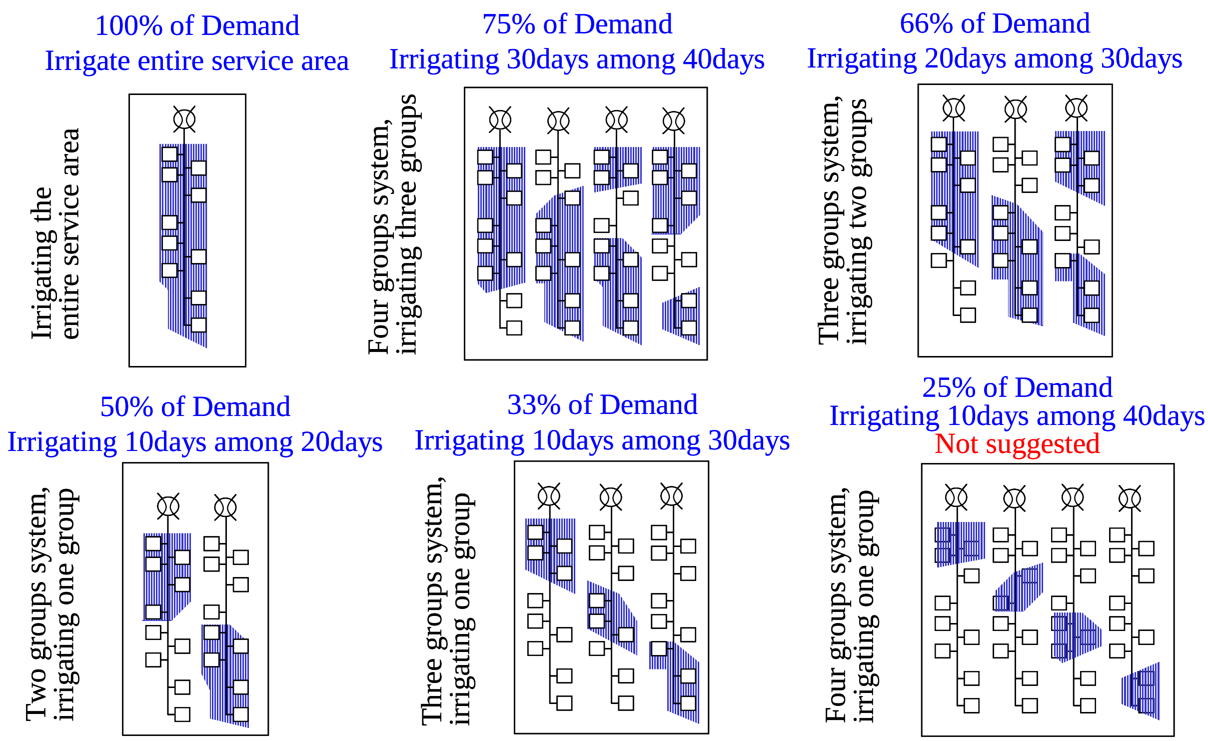


Figure 6. Example of Rotational Irrigation Applied to Lateral Canal System

Discussion on the Appropriateness of Past Transfer Cases

There are three types of transfer (or borrowing) of agricultural water: permanent, partial, and temporary transfers. After reviewing past cases regarding transfer of agricultural water in Taiwan, the following facts can be summarized:

1) Despite the fact that agricultural sector also faces water shortage, it is considered to be transferred whenever needed.

2) There is yet no reasonable compensation for the transfer of limited agricultural water resources.

3) The "value" of agricultural water resources is yet to be established.

4) Agricultural water right is seemingly abolished when frequent transfers are requested.

Basic principles on the aid of agricultural water to other sectors

Based on past experiences of water transfer, the following rules and basic principles are concluded:

First Ranked Domestic Sector During severe drought, the water resources is first re-allocated according to adjusted distribution. The first ranked domestic sector is eligible to transfer water from other lower ranked sectors when the necessary amount of water to sustain life and living needs is not acquired, and agricultural sector is always the one. However, proper compensation is needed as agriculture itself is also damaged from drought.

Second Ranked Agricultural Sector As the second ranked sector, the agricultural water is eligible to request transfer from lower ranked sectors. Although it rarely occurs, it is possible under food shortage conditions. In very few cases, it did happen when agricultural water requested aid from local deep wells of other sectors. However, the aid did not quite follow the priority order, and the compensations were based on negotiations.

Third Ranked Industrial Sector Industrial water ranks third behind domestic and agricultural. Nonetheless, in order to protect industrial development, which has higher production value and is more vulnerable to water shortage, the transfer from agricultural sector often occurs. And most of the cases were proceeded through negotiations with agricultural sector, yet the reasonable compensation for the damage loss of farmers is yet to be determined.

THE ACCESSION OF TAIWAN TO WTO ISSUE

As for environmental changes, the impact of the accession of Taiwan to WTO would be discussed specifically in this article. The World Trade Organization (WTO) is a global international organization dealing with the rules of trade between nations. At its heart are the WTO agreements, negotiated and signed by the bulk of the world's trading nations and ratified in their parliaments. The goal of WTO is to help producers of goods and services, exporters, and importers among its members conduct their business. Taiwan joined WTO in 2002, and under the agreement, 144,270 tons of rice were imported, resulting in a decrease in rice cultivation area through fallowing or crop-change. Thus, this issue raised another question on whether and how irrigation water could be saved. A management scheme in order to save irrigation water which could be used for other purposes is proposed.

Since the accession to the WTO, the cultivation land area of rice in Taiwan has been decreasing as the rice demand is decreased. It is studied and suggested in this article that land fallow and crop-change could be properly practiced on irrigation systems during water-shortage periods, which are commonly the first crop of rice in Taiwan. Under these practices, the agricultural water should be able to be effectively saved, and the non-agricultural demands could be supported without impacting food policies. The pressure of water-resources development could thus be reduced.

The focus of the study area in this article is conducted in Tao-Yuan area (Table 1), which is located in the northern part of Taiwan. The strategies for temporary shift of agricultural water under the conditions of maintaining the re-planting capability of farmland would be assessed.

Table 1. Rice Cultivation Area in Tao-Yuan Irrigation Association

year	crop	planned irrigation area(ha)	actual rice cultivation area(ha)	fallow and crop-change area(ha)	remarks
2000	1st crop	25,964	22,378	3,586	
	2nd crop	25,964	20,911	5,053	
2001	1st crop	25,933	21,742	4,191	
	2nd crop	25,933	20,576	5,357	
2002	1st crop	25,054	19,879	5,175	
	2nd crop	25,054	17,212	7,842	
2003	1st crop	24,749	-	24,749	Irrigation was stopped in 1st crop in accordance with government policy, and actual cultivation area was not surveyed.
	2nd crop	24,749	6,063	18,686	Severe drought
2004	1st crop	24,524	937	23,587	Irrigation stopped
	2nd crop	24,524	6,171	18,353	

Source: Tao-Yuan Irrigation Association

Preparation of Fallow or Crop-change Plans

If the cooperation from the farmers is acquired, it is proposed that in accordance with the promotion of fallow as well as crop-change systems, the planned water-supply in the reservoir areas, especially the Tao-Yuan area in this article, could be theoretically reduced by the unit of check-gate operation. The objective of saving water through fallow as well as crop-change in order to comply with WTO agreement could be reached by conveying it along the irrigation systems to the designated location or facility.

In order to effectively carry out the ideas of the study objectives, the following basic principles are first proposed:

1. Current planting systems should be maintained to avoid complexity,
2. The issue of water-right change should not be involved in order to minimize doubt as well as arguments, and
3. The form of "group fallow" should be promoted in order to effectively save water.

Hence under principle 1, the double-crop fields are suggested in order to maintain current planting system. Under principle 2, rotational fallow by groups are suggested in order not to involve the doubt of water right change. Under principle 3, the lateral ditches as basic units are suggested in order to promote through groups.

In addition, since water resources agencies already have set related moving or transferring response procedures as well as measures for emergency droughts, the ideas in this article should be adopted to constantly support water supply in order to meet the policy of fallow as well as crop-change. Under this principle, water supply from reservoirs is suggested.

In the mean time, associate measures or principles should also be promoted, such as compensation to farmers, respect to management input of irrigation associations, etc. Also, current fallow as well as crop-change is promoted targeting on second crop in consideration of crop yield and quality. However, from the water-resources point of view, first crop is suggested due to wet seasons.

Analysis of water-saving potential by fallow and crop-change in Tao-Yuan area

Year 2004 of Tao-Yuan is chosen as case study when the allocated fallow area in accordance with the WTO regulation of rice import was 11,946 hectares in the first crop and 15,943 hectares in the second crop. Assuming that all the fallow area in Tao-Yuan County was completely applied in the irrigation district of Tao-Yuan Irrigation Association, and further the work stations of associate laterals were set as basic units by taking the on-site operation applicability into consideration, the potential water saving amount can be obtained by accumulating the amounts of distributed water of the corresponding lateral work stations under the priority of lower water distribution weights, which are the water requirements per unit area, unless minor necessary adjustments are needed.

Following the principle, the manage areas of work stations are accumulated in the order from Ta-Lun (laterals #6, 7, and 8-1), Hsin-Po (lateral #9), Tao-Yuan (lateral #1), Hsin-Wu (laterals #12, Keh-Ker-Gang Ditch, and 12-1), Ta-Yuan (laterals #3, 4, and 5), until Kuan-Yin (laterals #10 and 11) work station, in which the accumulated area of 11,959 hectares has reached the first crop fallow requirement of 11,946 hectares. Hence, the corresponding accumulated distribution water of $123.648*10^6$ m^3 is the potential amount of water saved for the first crop (Table 2).

Continuing the procedure, the Ta-Chu (lateral #2) and Tsao-Ta (lateral #8) work stations are selected when the accumulated area of 16,906 hectares is reached beyond the 15,943 hectare second crop fallow area, the corresponding $179.989*10^6$ m^3 is the potential amount of water saved for the second crop.

In other words, assuming that the guided fallow area of both first and second crops of year 2004 in Tao-Yuan area is completely applied in Tao-Yuan Irrigation Association irrigation district, and basing the calculation on the average distributed amount of water of the 2005 irrigation plan of Tao-Yuan Irrigation Association, a total of approximately $300*10^6$ m^3s of water saving potential for the whole year could be expected.

Preparation of fallow or crop-change measures

Furthermore, according to the estimation of water shortage of domestic water supply systems in Taiwan area for the year 2011 as provided by the Water Resources Agency, the medium growth demand in Tao-Yuan area is $1.29*10^6$ m^3 per day while the supply side is $1.10*10^6$ m^3/day, hence, a deficit of $0.19*10^6$ m^3/day should be supported form other sources before water-shortage crisis occurs.

Table 2. Calculation of potential amount of saved water in accordance with fallow in Tao-Yuan area

	1	2	3	4	5	6	7	8
canal	Work station	lateral	Irrigation area (ha)	Area by work station (ha)	Distributed water by canal ($10^6 m^3$)	Water distribution weighting ($10^4 m^3$/ha)	Accumulated area by weighting order	Accumulated potential saved water ($10^6 m^3$)
Tao-Yuan main canal	Tao-Yuan	#1	1,465.0	1,465.0	12.892	0.88(3)	3,979	33.614
	Ta-Chu	#2	2,663.0	2,663.0	27.878	1.05(6)	14,622	151.526
	Ta-Yuan	#3	416.0	1,964	3.793	0.99(5)	9,117	88.824
		#4	983.0		9.105			
		#5	565.0		6.569			
	Ta-Lun	#6	514.0	1,386	4.425	0.80(1)	1,386	11.061
		#7	714.0		5.586			
		#8-1	158.0		1.050			
	Tsao-Ta	#8	2,284.0	2,284.0	28.463	1.25(9)	16,906	179.989
	Hsin-Po	#9	1,128.0	1,128.0	9.661	0.86(2)	2,514	20.722
	Kuan-Yin	#10、11	2,842.0	2,842.0	34.824	1.23(7)	11,959	123.648
	Hsin-Wu	#1	1,675.0	3,174	18.210	0.96(4)	7,153	69.357
		Keh-Ker-Gang Ditch	1,317.0		16.313			
		#12-1	182.0		1.220			
	Hu-Kou	Kuang-Fu ditch	3,784.0	3,784.0	47.004	1.24(8)		
Total				22,155				

Suppose that $0.19*10^6$ m^3/day is needed for 180 days in a crop period, then $34.2*10^6$ m^3 of water is required for each crop. Take the associated planned distribution water amounts for each crop, as well as the administrative coordination in execution practice into consideration, then, various combinations which meet the $34.2*10^6$ m^3 requirement could be determined by further considering the manage areas of work stations as basic fallow unit, one crop per fallow term, and rotational fallow to assist agricultural water. Furthermore, for the applicability of practical execution to minimize the operation disputes as well as to raise the coordination efficiency, it is suggested that the three groups of up-stream, mid-stream, and down-stream are classified. The upstream group includes Tao-Yuan, Ta-Chu, Ta-Yuan, and Ta-Lun work stations, while the mid-stream includes Tsao-Ta, Hsin-Po, and Kuan-Yin work stations, and the down-stream group includes Hsin-Wu and Hu-Kou work stations (Table 3). For each group, the associated amount of saved-water from conducting fallow could meet the requirement, and hence could provide reference for rotation fallow.

CONCLUDING REMARKS

The increase in industrial and domestic water demand due to the development of economy as well as change in industrial structures has put pressure in the agricultural water sector. Moreover, as the development of water resources is becoming difficult, especially after joining

WTO, how to effectively distribute and manage water resources has become an urgent issue in Taiwan.

Although three issues are discussed in this article, problems concerning agricultural water sector are far more sophisticated. And as agricultural water used to account for most part of the water resources in Taiwan, a comprehensive water resources policy and regulations are needed.

Table 3. Suggested rotational fallow groups by work stations in Tao-Yuan area

canal	Work station	lateral	1st crop		2nd crop		Suggested group
			Lateral intake ($10^6 m^3$)	Intake subtotal ($10^6 m^3$)	Lateral intake ($10^6 m^3$)	Intake subtotal ($10^6 m^3$)	
Tao-Yuan main canal	Tao-Yuan	#1	8.05	42.60	6.79	37.16	Upstream group
	Ta-Chu	#2	15.64		13.26		
	Ta-Yuan	#3	11.71		10.35		
		#4					
		#5					
	Ta-Lun	#6	7.20		6.77		
		#7					
		#8-1					
	Tsao-Ta	#8	14.99	41.17	13.55	37.25	Mid-stream group
	Hsin-Po	#9	6.08		5.53		
	Kuan-Yin	#10、11	20.09		18.17		
	Hsin-Wu	#1	20.27	45.93	17.16	38.50	Downstream group
		Keh-Ker-Gang Ditch					
		#12-1					
	Hu-Kou	Kuang-Fu ditch	25.66		21.34		
Remarks		Under the basis that $0.19*10^6 m^3$/day is needed for 180 days in a crop period, thus $34.2*10^6 m^3$ of water is required for each crop.					

COPING WITH COMPETITION FOR WATER: AN ECONOMIC FRAMEWORK

Ernie Niemi[1]
Kristin Lee[2]
Tatiana Raterma[3]

ABSTRACT

The supply of water in the United States cannot meet all the demands for water-related goods and services. Consequently, different groups compete for water, reflecting the pattern of economic values, jobs, and incomes they associate with the different goods and services. As the economy evolves and the supply of water resources varies, this pattern changes, with some demands growing stronger while others weaken. Useful insights into how the competition is evolving can be gained by comparing commercial demands (irrigation, hydropower, etc.) with consumers' demands for goods and services that directly enhance their well-being. Recent events in the Klamath River Basin of Oregon and California illustrate the forces shaping the competition for water. Until recently, commercial demands linked to irrigation, hydropower, and waste disposal asserted dominant claims to water, but these now are being challenged by consumers' demands for fish habitat, recreational fishing, resources supporting indigenous cultures, and a healthy ecosystem. Evidence indicates these consumer-related demands may already have higher economic values and generate higher levels of jobs and incomes. Moreover, their economic strength seems likely to grow more rapidly for the foreseeable future. Hence, the evolving competition points toward sharp reductions in irrigation, the decommissioning of five hydroelectric dams, and improvements in water quality.

INTRODUCTION

In most times and places, the supply of water in the United States cannot meet all the demands for water-related goods and services. Consequently, different groups compete for water, reflecting the pattern of economic values, jobs, and incomes they associate with the different goods and services. As the economy evolves and the supply of water resources varies, this pattern changes, with some demands growing stronger while others weaken. An appropriately structured description of the competition for water resources provides a useful framework for understanding the economic costs and benefits of different water-allocation decisions. Recent events in the Klamath River Basin of Oregon and California illustrate the framework's usefulness.

[1] Ernie Niemi, Senior Policy Analyst and Vice President, ECONorthwest, 99 West 10th Avenue, Suite 400, Eugene, OR 97401. Email: niemi@eugene.econw.com.
[2] Kristin Lee, Senior Policy Analyst, ECONorthwest, 99 West 10th Avenue, Suite 400, Eugene, OR 97401. Email: lee@eugene.econw.com.
[3] Tatiana Raterman, Research Assistant, ECONorthwest, 99 West 10th Avenue, Suite 400, Eugene, OR 97401. Email: raterman@eugene.econw.com.

THE RELATIONSHIP BETWEEN NATURAL RESOURCES AND ECONOMY

In the United States, one could once conclude that there was no competition for natural resources. The resources were abundant, and the economy made use of the resources in limited ways. Jobs, wealth, and prosperity were derived from natural resources primarily through extractive industries that converted resources into commodities or via development industries that displaced natural resources with human-made assets, such as buildings, roads, and dams. Figure 1 illustrates this view, showing a tradeoff between the economy and the environment: natural resources can be used to produce a healthy economy or a healthy environment, but not both.

This view was predominant in the western U.S. until at least the early 1990s, when implementation of the federal Endangered Species Act resulted in dramatic—about 50 percent—reductions in logging in western Washington, Oregon, and northern California. At the time, there was widespread belief that the region's economic health depended heavily on the forest-products industry and, hence, as logging plummeted many in the region feared the economy would collapse.

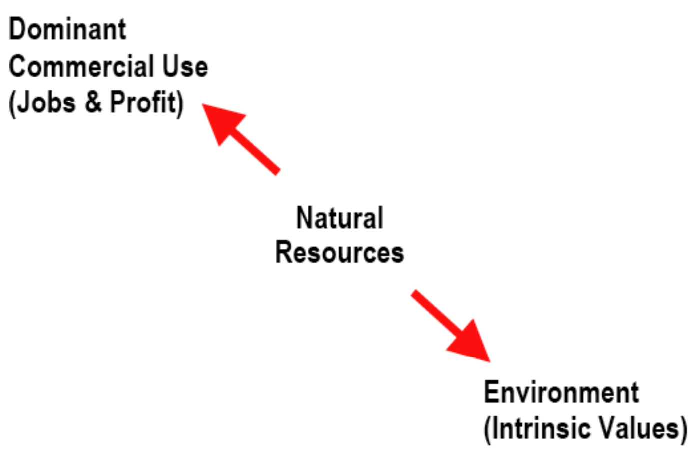


Figure 1. Competition for Natural Resources with Abundant Supply – Old View

The collapse never came. Instead, although employment in the forest-product industry declined by about 20,000, all but a few sections of the region experienced robust, prolonged economic growth (Niemi 2002). This outcome, and others that were similar, caused many to reevaluate and clarify the relationship between natural resources and the economy at the local, regional, and national levels. This effort has dismissed the view expressed in Figure 1 as simplistic and wrong (*see,* e.g., Goodstein 1999). There is not an on-off tradeoff between the economy and the environment with respect to the management and use of natural resources. Instead, there are multiple, competing ways in which natural resources can generate jobs, income, and increases in economic well-being. Some of these involve sacrifice of environmental quality, while others require a high level of environmental quality.

One could categorize this competition in any number of ways, but we have found it useful to employ a taxonomy that distinguishes among the four types of demand illustrated in Figure 2 (Courant et al. 1997). We call the two demands on the left side of Figure 2 demands for production amenities. These are demands for those goods and services that are, or could be, inputs to a process that produces other goods and services. The other two, which we call demands for consumption amenities, include demands for goods and services that directly enhance the well-being of consumers.

To facilitate the discussion, we assume that one type of demand, which we call the dominant commercial demand, prevails and then look at the consequences for the others. Moreover, we initially describe the consequences by portraying the competitors in the classic posture, with insular and adversarial interests, so that when one successfully secures the use of a natural resource, others are left wanting. From this perspective, people face stark, either-or choices: they can use water and related natural resources to produce either the goods and services associated with agriculture, hydropower, and other commodities or the goods and services associated with clean water, recreational opportunities, and other amenities, but not both.

In some circumstances, such tradeoffs dominate. In others, however, they do not. Hence, later in our discussion we recognize that the competing demands often overlap, with individuals, families, businesses, and communities wanting more than just one good or service from natural resources. Farm families, for example, typically want to use their land and water to produce both crops (or livestock) and a healthy, pleasant environment. Many urban residents want both clean water in streams and irrigation water to support a healthy agriculture industry. In this context, some landowners and water managers may be able to use these resources to produce multiple outputs, some of which are linked to commodity-driven growth and others to amenity-driven growth.

Competition for Production Amenities

On the left side of Figure 2 we place the competing demands for production amenities, i.e., elements of an ecosystem that facilitate commercial production. Farming, ranching, sand and gravel mining, and urban development are the most important of these demands. Demand for production amenities comes from private and public enterprises, which we define broadly, to include farming, ranching, private corporations, incorporated cities, and public agencies, as well as some households, such as those that develop new housing.

We separate the demands for production amenities into two groups. One of these, shown in the upper left of Figure 2, directly uses land and/or water; and they have dominant resource-use characteristics. This type of demand usually is associated with a familiar industry, such as farming or ranching, or with common urban-development activities. In general, only one product benefits from a particular use of a resource, but sometimes there may be more. A dam and reservoir may benefit anglers, irrigators, and consumers of hydroelectricity, for example.
These days, the dominant commercial use of a natural resource often imposes costs on other enterprises, which are represented in the bottom left of Figure 2. When irrigators deplete stream flows or reservoirs and reduce fish habitat, for example, they may reduce the production of

irrigators downstream who now have less water for their fields, impose costs on fishing guides who now have fewer prime fishing spots for their customers, or cause industrial water users in a downstream municipality to pay higher costs to remove pollutants from agricultural runoff.

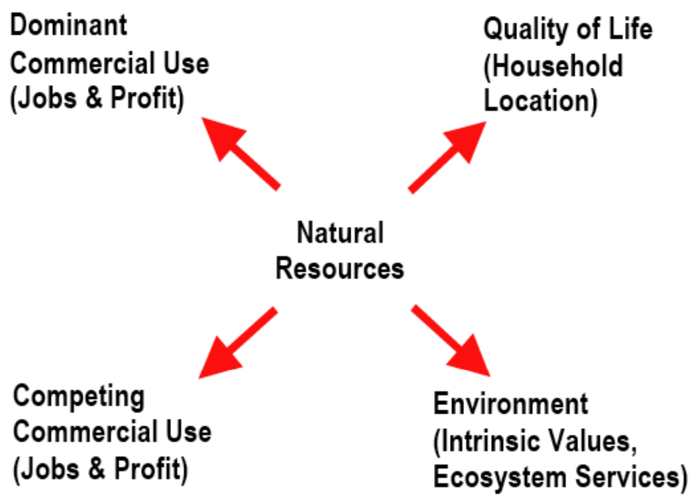


Figure 2. Competition for Natural Resources with Scarcity – Current Reality

We purposefully separate the demands on the left side of Figure 2 into two groups to drive home the message that there may be competition within the commercial sectors for land and water resources. We do so because often people perceive that the competition for natural resources occurs only between a single commercial interest and environmental-protection interests. By highlighting the existence of competition within the commercial sectors, we emphasize the point that the positive consequences arising from one set of commercial activities frequently have offsetting, negative effects on others.

Competition for Consumer Amenities

On the left side of Figure 2, natural resources are economically important because they are inputs in the production of other things, such as beef and hydroelectricity, that consumers want to have. On the right side, consumers' connection to these resources is more direct. That is, the resources are economically important for how they directly contribute to consumers' well-being. In economics parlance, such contributions are called consumption amenities. We distinguish between two types of demand for resource-related consumption amenities: one affects residential location decisions; the other does not.

Some resource-related goods and services, such as recreational opportunities and scenic vistas, contribute directly to the well-being of people who have access to them. Their contribution to consumers' well-being makes them economically important in their own right, but they are more important when they also influence the location decisions of households and businesses. We show the demands for consumption amenities that influence location decisions in the upper right portion of Figure 2.

Economists' explanation of why some consumption amenities can influence location revolves around the concept of consumer's surplus. Whenever a consumer derives benefits (increases in well-being) from a good or service that exceed the costs he or she pays to obtain it, the net benefit represents a net increase in well-being. This increment is called consumer's surplus.

In general, the nearer people live to resource-related amenities, the better their access, and the lower their cost of taking advantage of them. Thus, consumers can increase their consumer's surplus—their economic well-being—by living near locations that offer recreational opportunities, pleasant scenery, wildlife viewing, and other amenities. This consumer's surplus is, in effect, a *second paycheck* residents receive from living in a place where they have easy access to these amenities. Thus, the total welfare of residents near them is the sum of this second paycheck plus the purchasing power of the money income they receive from their first paycheck. Spatial differences in the size of the second paycheck affect behavior by influencing households to locate in one place rather than in another.

Quality-of-life values can be powerful. Many households that move into Oregon, for example, say they do so largely to take advantage of the state's quality of life, often accepting a reduction in income to do so (Judson et al. 1999). Some undoubtedly could enjoy higher earnings (their first paycheck) living elsewhere, but choose not to do so because they believe they can increase their total welfare (the sum of the first and second paychecks) by moving to Oregon. Some aspects of this quality of life—the strength of its communities, schools, and churches, for example—are not directly related to natural resources. But others are: the open space, outdoor way of life, and opportunities for fishing and hunting, to mention a few. All else equal, if the state's resource-related consumption amenities improve, some people already in the state will have a greater tendency to stay and additional people will tend to move in. Degradation of the amenities will have the reverse impacts.

Because quality-of-life values do not materialize in easily recognizable forms they are often overlooked. Studies that measure the output, jobs, incomes, and taxes generated when resources are used to produce crops and other commodities, for example, generally are blind to the output, jobs, incomes, and taxes that could have been generated had the resources been used to produce quality-of-life amenities that attract households. By their nature, such studies focus on the value of marketed goods and services (crops, livestock, etc.) and on the first paychecks commodity-oriented industries pay workers. Calculating the economic importance of quality-of-life amenities, in contrast, requires a different approach using different data and different analytical techniques. First, they must examine the value of the nonmarketed goods and services (scenic views, fish habitat, etc.) that constitute the amenities. That is, they must determine the size of the second paycheck enjoyed by nearby residents. Second, they must determine the extent to which the amenities influence household-location decisions. Third, they must examine the extent to which the influence on households stimulates commercial output, jobs, incomes, and the like.

The lower right portion of Figure 2 represents demands associated with economic values that do not necessarily entail a conscious, explicit use of natural resources. We call these environmental values. There are two general categories: nonuse values and values of goods and services that generally go unrecognized.

Nonuse values arise whenever individuals want to maintain some element of the environment, even though they do not directly or personally use it and have no intention to do so.[4] Sometimes this value is linked to the existence of a species, a scenic landscape, or other resource. It also can be associated with maintaining a particular cultural or ecological characteristic of a resource. Nonuse values also arise when people place a value on ensuring that a particular resource will be available for future generations. For example, a person might be willing to pay some amount to ensure that their grandchildren will have the same opportunities they've had to enjoy a free-flowing river, to see an open prairie or a traditional ranching landscape, or to go fishing. Similarly, some may desire that soils and water resources be used in a sustainable manner, so future generations will have opportunities to farm or ranch and pass along a legacy comparable to what exists today.

Ecosystems can provide goods and services that people consume without being aware of them. Some of these are part of the so-called web of life: operating at local, regional, and global scales, they help sustain human and other life not just in the immediate vicinity but farther afield, even globally. Others have a more direct link to the well-being of nearby residents, as when the microorganisms of an out-of-sight aquifer help purify water before it reaches the intake of a municipality's water utility. Even though people might not consciously consider the benefits of these services on a day-to-day basis, they probably would do so if they had a better understanding of them or if the services were to become threatened or noticeably diminished. Many people today, for example, consciously consider the economic values associated with the services produced by the global climate, in ways that were unknown, except to scientists, just a few years ago. Some scientists and economists believe many more services have great economic value although this value and, hence, the demands for the services are not visible (*See*, e.g., Daily 1997).

Unlike the other types of demand in Figure 2, demands related to environmental values do not necessarily affect population growth, jobs, income, or other indicators of economic activity in the local economy. Residents of Sacramento, for example, might place a value on and, hence, express a demand for protecting the existence of sea otters harmed by the *Exxon Valdez* oil spill in Prince William Sound, Alaska, but this demand might never result in any discernible change in economic activity. Then again, some changes might occur. Those wanting to ensure the otters' existence might trigger protective actions by donating money, pressing for the expenditure of public funds, or lobbying for regulations toward that end. The resulting changes in the management of the otters' habitat might generate jobs and incomes, and the improvements in habitat might, in turn, be seen as quality-of-life amenities that influence household locations and generate further economic activity in nearby communities.

Similarly, demands for environmental goods and services might manifest themselves as people become aware of their importance or of a threat to them. The Conservation Reserve Program and other federal programs that pay farmers to protect and enhance environmental resources on their properties, for example, came into place as the American public realized the importance of these

[4] These values are also known as passive-use values or intrinsic values.

resources, and the payments help farmers and generate jobs and incomes in rural communities (*See*, e.g., Feather et al. 1999, and Sullivan et al. 2002).

Relative Strength of the Competing Demands

In the distant past, commercial demands outweighed any others and in some places this remains true. For most of the western U.S., however, times have changed and mounting evidence suggests that in many locations the demands on the right side of Figure 2 are similar in size to or larger than those on the left, and growing faster. Recent studies in Washington's Columbia River Basin provide instructive insights. If one considers only the direct benefits to farmers who would use the water, diverting more water from the river to irrigate crops in the basin would generate net benefits ranging from negative $91 to positive $147 per acre-foot (Huppert et al. 2004). For many crops, however, the increased production would reduce market prices, so other farmers would experience a loss. Overall, an increase in irrigation would cause farmers throughout the state to experience a loss of at least $60 per acre foot (Williams and Capps 2005). Leaving the water in the river, however, would yield multiple benefits: additional generation of hydropower worth up to $37/acre-foot; improvements in navigation worth $6/acre-foot; and general recreation, worth $8 – $130/acre-foot (Huppert et al. 2004). Additional benefits would arise insofar as leaving water in the river would preclude increases in farm-runoff pollution, improve habitat for salmon and steelhead, enhance the productivity of the riverine ecosystem, and assimilate waste, but these have not been quantified on a per-acre-foot basis. Taken together, these findings strongly suggest that leaving additional water in the river would have a net economic benefit, and that the competing demands are stronger than the historically dominant, commercial demand from irrigated agriculture.

Findings in the Central Valley of California support similar conclusions. Analysis in 1997 found that the marginal cost to irrigators of providing additional water to meet fish and wildlife objectives would be about $100 per acre-foot (Congressional Budget Office 1997). In contrast, a survey of California households suggests that water used to improve wetlands and to improve the salmon fishery has values of $6,100 and $41,000 per acre-foot, respectively (Loomis et al. 1991).

Consumer amenities also can exert a powerful influence on local economic growth. Amenity-driven growth accounts for about one-half the interstate differences in job growth in the U.S. (Partridge and Rickman 2003). Natural-resource amenities are especially important in western states, correlating with growth in population, jobs, income, and entrepreneurial activity (*See*, e.g., McGranahan 1999). Shumway and Otterson (2001) found that counties with concentrations of recreational and scenic amenities had more robust growth that those with high concentrations of agricultural, mining and manufacturing, or government. Conversion of one acre of developable pasture land in Maryland to conservation land increases the average value of neighborhood residential properties by $3,307 (Irwin 2002).

Amenities are important to local economies not just in the mountains and along the coast but also in the Midwest farm belt. Even in Nebraska, a state dominated by private property (97 percent of the total) and agricultural activities, the value (consumer surplus) of fishing, hunting, and wildlife-watching—but not including boating and other resource-related recreation—was about

40 percent of the value (net earnings) of agriculture in 2002 (Niemi et al. 2006). The actual difference probably is smaller insofar as the agricultural value does not account for extensive costs farms and ranches impose on others through pollution, the destruction of wildlife habitat, and the dewatering of streams. About half the Iowans responding to a survey said the lake nearest them was very or somewhat important in determining the economic vitality of their community, making the community an interesting or vibrant place in which to live, and attracting and retaining young people. About one-third said the nearest lake was very or somewhat important in helping employers attract and retain a skilled workforce and influencing the decisions of businesses to locate or expand locally (Azevedo et al. 2003). In Wisconsin, a partial accounting of the economic benefits of incorporating cropland into a fish and wildlife refuge would exceed a partial accounting of the costs (lost net farm revenue) 2 – 5 times; for pasture the partial benefits would exceed the partial costs 8 – 20 times (Malloy et al. 1998).

Environmental values also can be large. The marginal value of changes in salmon and steelhead populations in the Columbia River is $715 per fish (Huppert et al. 2004). Most of this value represents nonuse values associated with preventing the extinction of the fish themselves as well as with enhancing and sustaining a healthy ecosystem. Analysts in the Puget Sound area found that the “whole system” value of the flood protection provided by some wetlands are as high as $51,000 per acre, reflecting both their efficiency in attenuating flooding and their replacement cost (Leschine et al. 1997). Other research documents the value of other goods and services provided by wetlands, such as recreational opportunities and wildlife habitat (Woodward and Wui 2001, and Heimlich et al. 1998). Ecosystems that provide communities with high-quality water for municipal-industrial use give residents an opportunity to save about $25 per person in water-treatment costs (Hulse et al. 2002).

APPLYING THE FRAMEWORK TO THE KLAMATH RIVER BASIN

The Klamath River Basin spans the border of Oregon and California, as shown in Figure 3. The Upper Basin includes the area in Oregon, with some parts of California, that lie upstream of the border. There are six dams on the river, from Upper Klamath Lake to Iron Gate Dam, just south of the border. Water throughout the basin is heavily affected by the Klamath Reclamation Project in the Upper Basin. The Klamath Reclamation Project drained and converted to agricultural use approximately 40,000 acres, created three storage reservoirs with 1,104,418 acre-feet of active storage, and built more than 1,400 miles of canals and drains, 37 pumping plants, and 2 tunnels to deliver water to irrigators. The project can provide water to 240,000 acres of irrigable land and to 86,000 acres in four national wildlife refuges. Fisheries in the Lower Basin, downstream of the state border, historically supported tribal and non-tribal communities along the river as well as along the California and Oregon coast. Iron Gate Dam blocks the passage of fish between the Lower and Upper Basins.

Events in 2001 and 2002 highlight the competing demands for water in the Klamath Basin. After a winter that delivered only about 30 percent of the normal snowfall in the Upper Basin, the Bureau of Reclamation, the federal agency that manages the Klamath Project, notified farmers in April of 2001 that it would not deliver water. The agency could not provide water, because it needed to comply with the obligations to operate in a manner that would not harm coho salmon, which had been listed in 1997 as a threatened species under the federal Endangered Species Act.[5] The decision affected about 1,200 farms and 85 percent of the lands that typically had been irrigated with water from the Klamath project.

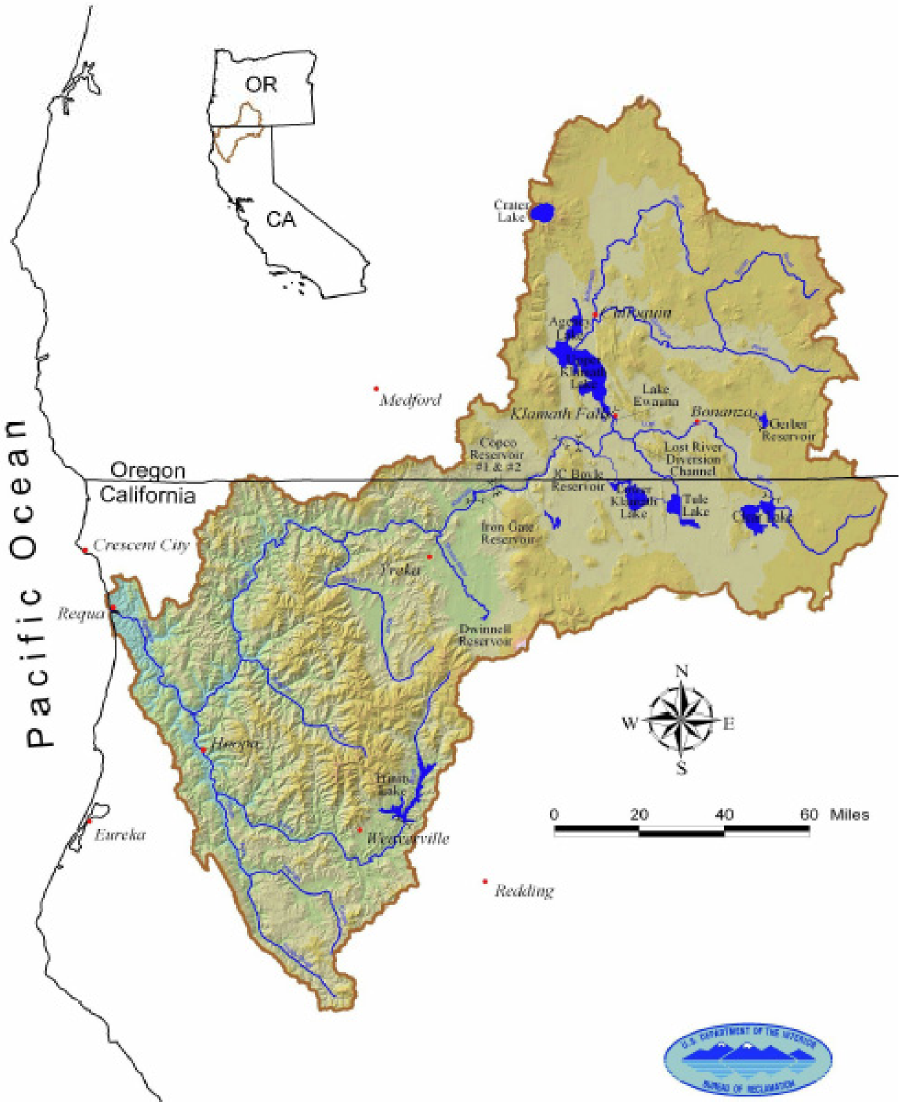


Figure 3. Klamath River Basin
Source: U.S. Department of Interior (1999).

The affected farmers, and many others, were outraged. The anger had many facets, but much of it stemmed from a belief that the relationship between the water and the economy is as shown in Figure 1. Irrigation has been the dominant commercial demand for water for the past century.

---

5 The Bureau also has an obligation to protect two species of fish in the Upper Basin, the Lost River and shortnose suckers, which were listed as endangered under Act in 1988.

Both farmers and many others believed that the basin's water could generate economic benefits only if it were diverted to irrigate crops, and that using the water for irrigation would have no economic downside. For them, leaving the water in the river was an unfathomable decision to prefer the environment over economic welfare. A common assertion was that the action would cause farmers to lose $250 million and destroy the local economy in the blink of an eye. Opposition to the decision became a focal point for people throughout the U.S. with negative views toward the Endangered Species Act and other environmental regulations. Many agreed when a leading law-enforcement official tagged those who supported leaving water in the river as economic terrorists.

Extensive evidence and actual events reveal a water-economy relationship in the Klamath Basin that is consistent not with Figure 1 but with Figure 2. Although some farmers suffered considerable economic losses in 2001, others did not. A tax accountant who handles financial records for many irrigators in the Klamath Project reported that, although 40 – 50 percent of them suffered financial losses, 20 percent experienced average financial performance, and 30 – 40 percent of them had an excellent year (Jaeger 2002). This distribution of outcomes is not surprising. The 1997 agricultural census found that for Klamath County, Oregon, the economic center of the Upper Basin, 37 percent of farms experienced net losses of $19,139, while the remaining farms had net gains of $70,373 (U.S. Department of Agriculture 1999). Moreover, as Table 1 shows, the agricultural sector has exhibited weak financial performance for decades. Within Klamath County both agricultural employment and income have declined as a percentage of the county's total and, in 1998, the overall income of farm proprietors was negative. These and similar data suggest that, even if the Bureau of Reclamation had not decided to leave water in the river in 2001, many farms in the Basin, and perhaps the farm sector as a whole, would have lost money. As things turned out, with assistance from federal agencies and other sources, it is not clear that irrigators in the Klamath Project experienced any change in overall net farm revenues (Jaeger 2002). In sum, the dominant commercial demand from irrigators for water in the Klamath Basin is diminishing in its overall importance to the surrounding economy.

Table 1: The Farm Sector's Share of Total Employment and Income in Klamath County

	1970	**1980**	**1990**	**1998**
Employment	14%	11%	11%	10% [a]
Income	8%	6%	1%	0.5% [b]

Source: ECONorthwest with data from the Bureau of Economic Analysis.

[a] Proprietors constitute 4% and employees 6%. Total employment (including proprietors) in Klamath County was 32,234.

[b] Reflects the net farm-sector income, comprised of earnings by employees of $9 million and a loss of $3 million by proprietors. Total income for Klamath County was $1.25 billion.

Events in 2002 sharply demonstrated the existence of competing demands for the basin's water. With intervention by the White House and considerable fanfare, the Bureau of Reclamation opened the headgates and delivered water to irrigators in the Klamath Project in the spring, even though water supplies in the Upper Basin remained below normal. Attention died down until September, when more than 30,000—some say 80,000—salmon died near the mouth of the

Klamath River. Although too little is known about the river's physical and biological characteristics to explain the fish kill fully, biologists with the State of California and others concluded that the diversion of water to irrigators played a critical role, by reducing flows so the salmon clustered close together, where they were attacked by pathogens.

The fish kill, itself, had an adverse economic effect on tribal members who would have fished for them, used them to supplement their families' diet, and sold some of them commercially. It also adversely affected non-tribal, recreational anglers. The fish kill also had a legacy effect, insofar as the dead fish were unable to spawn, and the reduced size of the next generation has caused fishery managers to restrict commercial fishing for all salmon along the California and Oregon coast wherever fishing would threaten to reduce further the Klamath River population. The curtailment of fishing has reduced incomes and had detrimental effects on economic activity in fishing communities along the coast.

Douglas and Sleeper (2002) show that recreational demands for water in the basin could far outstrip the commercial demands of irrigators, hydropower generation, commercial fishing, and others. Simulating the ecosystem's ability to produce salmon, absent these commercial activities, and estimating the recreational value of the increased salmon runs, they concluded that this value would be about 9 times the net value commercial activities derived from the basin's water. Just within the context of irrigated agriculture, this finding seems plausible, insofar as much of the irrigation producers' net earnings have been declining, and these do not fully account for other, spillover costs. It also seems plausible in the context of another major commercial use of water, hydropower generation. State and federal regulators are pressing the owner of hydropower dams on the Klamath River to modify them so salmon and other species can move past them both upriver and downriver, and the owner has indicated that it would be cheaper to remove the dams.

CONCLUSION

Many have recognized the importance of the competing demands for water. The 1992 International Conference on Water and Environment in Dublin, Ireland, for example, developed a set of four principles to guide management of freshwater, the first of which is "Water has economic value in all its competing uses and should be recognized as an economic good."[6] A recent report by the National Research Council also demonstrates the importance of making management decisions regarding water resources based on a full valuation of all the goods and services that would be affected (National Research Council 2004). These and similar admonitions can have little effect, however, when there exists too little information to determine the value of many, if not most, of the goods and services, or if decision-makers care not about these values but about the impacts on jobs, incomes, and the like. Such settings, which, in our

---

[6] World Meteorological Organization. Retrieved February 28, 2007, from website http://www.wmo.ch/web/homs/documents/english/icwedece.html. The other principles are: (1) Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment; (2) Water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels; (3) Women play a central part in the provision, management and safe-guarding of water.

experience occur more frequently than not, embody the built-in bias favoring continuation of dominant commercial uses of water resources, insofar as the economic data regarding these far surpass the data regarding competing demands.

We offer a framework that we have found effective in clarifying the net effects of water-management decisions because it begins by recognizing that there exists competition for these resources. Once decision-makers accept this fact (and more and more do) they then can consider the available information regarding each—regardless of disparities in the type and reliability of the information—and reach conclusions about the likelihood that one type of demand is larger than or is growing faster than the others.

REFERENCES

Azevedo, C.D., K.J. Egan, J.A. Herriges, and C.L. Kling. 2003. *The Iowa Lakes Valuation Project: Summary and Findings from Year One*. Iowa State University Department of Economics and Center for Agricultural and Rural Development. August 27. Retrieved August 8, 2005, from http://www.card.iastate.edu/environment/items/IowaLakesReport.pdf.

Congressional Budget Office. 1997. “Quantitative Analysis of the Central Valley Project Improvement Act.” In *Water Use Conflicts in the West: Implications of Reforming the Bureau of Reclamation's Water Supply Policies*. Retrieved February 28, 2007, from http://www.cbo.gov/showdoc.cfm?index=46&sequence=6.

Courant, P.N., E. Niemi, and W.E. Whitelaw. 1997. *The Ecosystem-Economy Relationship: Insights from Six Forested LTER Sites*. ECONorthwest for National Science Foundation.

Daily, G.C. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington, D.C.: Island Press.

Douglas, A.J. and A. Sleeper. 2002. *Estimating Recreation Trip Related Benefits for the Klamath River Basin with TCM and Contingent Use Data*. Midcontinent Ecological Science Center, U.S. Geological Survey.

Feather, P., D. Hellerstein, and A.J. Hansen. 1999. *Economic Valuation of Environmental Benefits and the Targeting of Conservation Programs.* U.S. Department of Agriculture, Economic Research Service. No. AER-778. April

Goodstein, E. 1999. *The Trade-Off Myth: Fact and Fiction about Jobs and the Environment*. Washington, D.C.: Island Press.

Heimlich, R.E., K.D. Wiebe, R. Claassen, D. Gadsby, and R.M. House. 1998. *Wetlands and Agriculture: Private Interests and Public Benefits.* Economic Research Service, U.S. Department of Agriculture. Washington, D.C. Agricultural Economic Report 765.

Hulse, D., G. Grant, E. Niemi et al. 2002. *Muddy Waters: How Floods Clarify Evolving Relationships Among Landscape Processes and Resource Management Decision-Making in Municipal Watersheds*. National Council on Environmental Research and Quality Assurance, U.S. EPA GAD # R825822.

Huppert, D., G. Green, W. Beyers et al. 2004. *Economics of Columbia River Initiative*. Washington Department of Ecology and CRI Economics Advisory Committee. January 12.

Irwin, E.G. 2002. "The Effects of Open Space on Residential Property Values." *Land Economics* 78 (3): 698-704.

Jaeger, W.K. 2002. "What Actually Happened in 2001? A Comparison of Estimate Impacts and Reported Outcomes of the Irrigation Curtailment in the Upper Klamath Basin." In W. Braunworth Jr., T. Welch, and R. Hathaway, eds., Water Allocation in the Klamath Reclamation Project, 2001: An Assessment of Natural Resource, Economic, Social, and Institutional Issues with a Focus on the Upper Klamath Basin. Corvallis, OR: Oregon State University. Pp. 265-284.

Judson, D.H., S. Reynolds-Scanlon, and C.L. Popoff. 1999. "Migrants to Oregon in the 1990's: Working Age, Near-Retirees, and Retirees Make Different Destination Choices." *Rural Development Perspectives* 14 (2): 24-31.

Leschine, T.M., K.F. Wellman, and T.H. Green. 1997. *The Economic Value of Wetlands: Wetlands' Role in Flood Protection in Western Washington*. Washington Department of Ecology, Publication No. 97-100.

Loomis, J., M. Hanemann, B. Kanninen, and T. Wegge. 1991. "Willingness to Pay to Protect Wetlands and Reduce Wildlife Contamination from Agricultural Drainage." In A. Dinar and D. Zilberman, eds., *The Economics and Management of Water and Drainage in Agriculture*. Boston: Klumer Academic Publishers. 411-429.

Malloy, S.J., R.E. Unsworth, and E.A. Blomdahl. 1998. *Economic Assessment for the Necedah National Wildlife Refuge Comprehensive Conservation Plan*. U.S. Department of Interior, Fish and Wildlife Service. March. Retrieved December 10, 2005, from http://www.indecon.com/NWR%20Economic%20Analyses/Necedah_NWR.pdf.

McGranahan, D.A. 1999. *Natural Amenities Drive Rural Population Change.* U.S. Department of Agriculture, Economic Research Service, Food and Rural Economics Division. Agricultural Economic Report No. 781. September.

National Research Council, Committee on Assessing and Valuing the Services of Aquatic and Related Terrestrial Ecosystems. 2004. *Valuing Ecosystem Resources: Toward Better Environmental Decision-Making*. National Academies Press.

Niemi, E. 2002. "The Sky Will Not Fall: Economic Responses to Protection of At-Risk Species and Natural Ecosystems." *Fisheries* 27 (1): 24-28.

Niemi, E., C. Neculae, and T. Raterman. 2006. *Natural Resource Amenities and Nebraska's Economy: Current Connections, Challenges, and Possibilities.* Nebraska Game and Parks Commission. Retrieved February 28, 2007, from http://www.ngpc.state.ne.us/admin/niemereport.pdf.

Partridge, M. and D. Rickman. 2003. "The Waxing and Waning of Regional Economies: The Chicken-Egg Question of Jobs Versus People." *Journal of Urban Economics* 53: 76-97.

Shumway, J.M. and S.M. Otterson. 2001. "Spatial Patterns of Migration and Income Change in the Mountain West: The Dominance of Service-Based, Amenity-Rich Counties." *Professional Geographer* 53 (4): 492-502.

Sullivan, P., D. Hellerstein, L. Hansen, R. Johansson, S. Koenig, R.N. Lubowski, W. McBride, D.A. McGranahan, M.J. Roberts, S. J. Vogel, and S. Bucholtz. 2002. *The Conservation Reserve Program: The Implications for Rural America*. U.S. Department of Agriculture, Economic Research Service. Agricultural Economic Report 834. September.

U.S. Department of Agriculture, National Agricultural Statistics Service. 1999. *1997 Census of Agriculture: Oregon*.

U.S. Department of Interior, Bureau of Reclamation, Klamath Basin Area Office. 1999. *Klamath River Basin*. Map. Compiled by M. Newman. Retrieved May 29, 2007, from http://www.usbr.gov/mp/kbao/maps/1_basin.jpg.

Williams, G.W. and O. Capps, Jr. 2005. *An Assessment of Future Markets for Crops Grown Along the Columbia River: Economic Implications of Increases in Production Resulting from New Agricultural Water Rights Under the Columbia River Initiative*. Texas Agribusiness Market Research Center and American Rivers, Inc. September. Retrieved October 27, 2006, from http://www.americanrivers.org/site/DocServer/WilliamsCappsFinalStudy.pdf?docID=3241.

Woodward, R.T. and Y.S. Wui. 2001. "The Economic Value of Wetland Services: A Meta-Analysis." *Ecological Economics* 37 (2): 257-270.

ALLOCATION OF WATER USE RIGHTS IN IRRIGATED AGRICULTURE: EXPERIENCE WITH DESIGNING INSTITUTIONS AND FACILITATING MARKET PROCESSES IN SOUTH AFRICA

Gerhard R. Backeberg[1]

ABSTRACT

Irrigated agriculture uses the biggest share of surface and underground water resources for food production in local and export markets. Given the competing demands from domestic and industrial uses, economic pressures exist to increase the efficient allocation and conservation of water. A political-economic analysis found that institutional change is required to establish correct incentives and effective market processes. This change was brought about by acceptance of a constitution and promulgation of a new national water act. In the democratic political order, everyone now has the constitutional right of access to sufficient water. The obligation rests on the government to take reasonable measures within available resources for progressive realization of these rights. This is done through water allocation reform and implementation of the national water resource strategy. It involves compulsory licensing of water use for irrigation to achieve an equitable initial apportionment of water use rights. Water conservation and demand management measures are further being implemented to increase the efficiency of water use and the re-allocation of water entitlements from lower to higher valued uses within or between different economic sectors. The legal framework has created conditions which enable market trades of water use rights. Substantial market transactions have been recorded, with most of these trades occurring in irrigation areas along the Orange River. Indications are that the market process provides opportunities for the more efficient use of water. Based on investigations of these transactions, institutional requirements are specified which will improve the performance of market transfers of water use rights.

INTRODUCTION

In the industrialized economy of South Africa, the water requirements of irrigated agriculture are estimated at 56% of the total annual water requirements of 22 045 million m^3 surface and groundwater. Although the contribution of irrigation to total agricultural production varies according to crop type, most of this water is used for commercial food production in local and export markets. With increasing urbanization and higher standards of living, competing demands are experienced for domestic, mining and industrial water use (Backeberg and Odendaal, 1998: 49-55). Under conditions of general water stress and increasing scarcity, economic pressures exist for improved conservation and allocation of water resources (Goldblatt and Davies, 2002: 381-384). The obvious economic solution is the classic approach of efficient resource pricing and optimal allocation of water between alternative uses. However, the more fundamental question is about underlying conflicts, appropriate institutions, correct incentives and related

[1]Director – Water Utilisation in Agriculture; Water Research Commission; Private Bag X03, Gezina, 0031, Pretoria, South Africa; backeberg@wrc.org.za

decision-making processes to manage water allocation (Backeberg, 1994: 226-236; 1995: 165-175). A suitable framework is a hierarchy of decision-making on a policy, institutional and operational level within an integrated water system (Ciriacy-Wantrup, 1985: 67-75). Analysis of the political economy of irrigation policy in the pre-constitutional colonial and apartheid era of government found a preference for supply management through central bureaucratic control and reliance on legislative processes for the allocation of water resources. After evaluating political, bureaucratic and market processes, it was shown that the market process is the most effective for re-allocation of water, but it required institutional change. This was only possible through a change in water policies, which in turn required fundamental political and constitutional reform.

After establishment of the new Constitution (Republic of South Africa (RSA), 1996), a wide-ranging process of natural resource policy reform and review of water policy was initiated (Backeberg 1996a: 160-169; MacKay 2003: 49-83). Due to the legacy of political inequalities, one of the key drivers is to correct the unequal rights and access to land and water, as well as the related unequal economic opportunities and provision of services. In the new constitutional democratic order and with a market driven economy in South Africa, an analytical approach with a political economy perspective is again most relevant. It helps to understand the complex interactions between actors in the political, economic and social environment who participate in the process of reform (Reed, 2001:9). The political economy of water resource allocation gives attention to the dynamic interaction between social groups (black and white farmers); economic agents (subsistence and commercial households and firms); and government authorities (ministers and bureaucracies), in their effort to obtain power and create wealth. Following this method of analysis requires consideration of the decisions, actions and outcome of not only individual actors but also social groups; the different political, sociological, cultural and economic variables across these groups; and the institutional and market forces that influence the behaviour of people. The purpose of this paper is therefore to assess the progress which has been made towards instituting allocation reform and implementing market processes to achieve the desired direction of equitable and efficient allocation of water resources.

POLITICAL AND LEGAL NEGOTIATIONS: ESTABLISHING LEGITIMATE WATER RIGHTS

Theoretical Principles

Individuals take decisions on water conservation and allocation within an institutional framework, and thereafter follows individual or collective action. These institutions are the sets of ordered relationships amongst people which determine their rights and obligations and which affect their economic behaviour (Schmid 1972: 893; Bromley, 1989: 39-41). According to institutional economic thought, the issues of conflict, power and coercion in economic activities are a common theme (Schmid 1978: 3-12, 40-42). Scarcity implies a conflict over the control of natural resources and property rights are acquired for that reason. Power is unavoidable with differences between the capabilities and preferences of individuals and can be described or quantified in terms of the degree to which there is participation in decision-making or realization of own interests. Awarding or apportioning rights enable the recipients of rights the potential power to participate in decisions on the development, use and transfer of rights to resources.

Through voluntary negotiations and private transactions there is exchange over the control of resources and two-way coercion between the contracting parties. In administrative transactions based on government authority there is one-way coercion. Change in institutions or rights require a preparedness to at least change the distribution of power.

The policy issue is largely one of choosing the institutional form and arrangements for individual and collective decision and action in economic and political processes. Decision rules or strategies for conservation and allocation of water resources become more important as scarcity increases (Nanda, 1977: 135; Weatherford, 1982: 3-7). The essence of water resource management under these circumstances is more intensive utilization of the available water and transfer of rights to relative fixed flows and stocks of water between competing uses and users. In contrast to a structural engineering approach to increase water supply, institutions must be designed to find an alternative non-structural economic solution by managing both demand and supply and the conflict caused by water scarcity (Backeberg, 1996b: 326-328).

Conflict Over Water Use

The water problem is mainly one of managing conflict. Apart from the conflict due to scarcity, there is conflict between canal and pump operators on the same river; conflict between upstream and downstream water users; conflict between private and public interests; and in the case of South Africa there is conflict between black and white social groups who have access and who do not have access to water resources. This conflict has been documented in the early years of colonial rule (Jacobs, 2003: 57-60). Black people in the Kuruman area of the present Northern Cape Province were not accustomed to channeling water for crop cultivation and access to water was not the main consideration to choose sites for settlement and livestock herding. Irrigation was promoted after the arrival of missionaries of the London Mission Society but the first attempts were hampered by lack of rights to land and water. This involved disagreements and confrontations over the use of water for intensive irrigated crop production as opposed to extensive rain-fed crop production. Thereafter the missionaries (in the period 1821-1824) requested and received permission from the chief of the local tribe to use land for irrigation with payment of a nominal amount. The agreement had different meanings to both parties since according to African tradition it was granting of a use right to a subordinate while according to European custom the transaction was understood as transfer of ownership.

The conflict between the local black population and white farmer settlers has continued over successive governments with colonial, dominion and apartheid political ideologies. It has persisted up to the present period of democratic government and is manifested in two ways: First, on 16 million ha of communal land out of a total of 103 million ha grazing, forestry, arable and irrigated land (Hofstätter, 2007: 36-39; Nieuwoudt and Groenewald, 2003: x) tenure and legal security of water rights obtained by customary law or common law have apparently not been specified (Thompson, 2006: 104-107). This is in spite of the fact that communal land rights and riparian water rights are both common property, and should be compatible to determine access to rightfully use these resources. Second, settlement of black farmers on smallholder irrigation schemes over four eras of (i) peasant and mission diversion schemes; (ii) smallholder canal schemes; (iii) independent homeland schemes; and (iv) revitalization and irrigation management transfer, has culminated in development of 49 500 ha out of 1,3 million ha irrigation (Van Averbeke and Mohamed, 2006: 2-7). The extent of the conflict is also apparent when the large number of black subsistence farmers who control a relative small area of land and volume of water are compared to the small number of white commercial farmers who control most land and water (Backeberg, 2006: 2-3). Both these situations of insecure holding and inequitable distribution of water rights have been intensively investigated and reform is ongoing under the new constitutional dispensation.

Land and Water Allocation Reform

Before assessing the current state of reform, it is necessary to briefly refer to the historic evolution of water rights law in the context of irrigation development in South Africa (Backeberg, 2002: 65-94). Water law reflected the dual influence of Roman-Dutch and English common law. Since 1856 the riparian doctrine of reasonable and proportional common property rights to the flow of water in public rivers by a group of owners with private land rights, was the basis of the rights to surface water. For underground water, private rights by the land owner were applicable. Given the origin of these water laws and interpretation in a semi-arid country, legislative adjustments and restrictions on common law doctrines have progressively been placed on water rights after 1906, arguably based on the principle of water rights as public property and with the debatable intension to promote the public interest. According to the Water Act of 1956, various legislative controls and regulations applied within and outside declared government water control areas. Water rights were attenuated since the act specified that there are no ownership rights but only use rights to water and that a government department has the authority to allocate water rights.

Changing the Form of Water Use Rights: Fundamental and comprehensive review of water law was undertaken in terms of Sections 27(1)(b) and 27(2) in the Bill of Rights in the Constitution of South Africa (RSA, 1996) which states that "Everyone has the right to have access to sufficient food and water". The government "must therefore take reasonable legislative and other measures within available resources" for the progressive realization of these rights. This included the acceptance of Water Law Principles (Department of Water Affairs and Forestry (DWAF), 1996), formulation of a National Water Policy (DWAF, 1997) and promulgation of the National Water Act (RSA, 1998). (See De Coning and Sherwill (2004: 10-30) and Backeberg (2003: 154-163; 2005: 111-112), for an overview of the water policy process as well as irrigation policy and water institutional reform). In comparison with the previous legal dispensation, the national government continues to have the ultimate responsibility for the allocation and conservation of water according to the criteria of public interest, sustainability, equity and efficiency to achieve optimum long-term social and economic benefit for society. All water wherever it occurs in the hydrological cycle (presumably during the land phase) is considered as a resource common to all and will be subject to national control. The riparian principle was abolished and replaced by the reserve for basic human needs and ecological requirements, while all water uses shall be subject to an authorization and there shall be no ownership rights to water. According to Pienaar and Van der Schyff (2005: 264) "one of the main objectives of the National Water Act was to reform the water dispensation from one based on riparian ownership and ownership of land to one based on government allocation of water by balancing demand for and availability of water, the so-called licensing principle". As a transitional measure the National Water Act (NWA) permits existing lawful use to continue under approved conditions until it is formally licensed. The license to use water is specific to the user to whom it is issued and to a particular property; it is specific to the use for which it is issued; it is valid for a specified time period not exceeding forty years; it must be renewed every five years; and it may have a number of conditions attached to it (DWAF, 2004: 65-66).

The National Water Resource Strategy (NWRS) explains how the intentions of policy and enforceable legislative measures will be implemented. The process of compulsory licensing was specifically designed to correct the inequities of the past. The criteria for assessing compulsory licensing are set out in Section 43(1) of the NWA and the process involves the following (DWAF, 2004: 67-68).

- The lawfulness of existing use must first be verified;
- The responsible authority (i.e. the Department of Water Affairs and Forestry) issues a call for licensing to registered users, but must identify other prospective users, especially from marginalized or disadvantaged groups, who have not previously had access to water resources because of racially discriminatory legislation, to ensure that water is allocated fairly.
- The existing users and prospective users must submit license applications which are evaluated by the responsible authority.
- The water requirements based on application and claims for licensing are reconciled with water availability and possible solutions are developed to find a balance between requirements of the Reserve, water quality, application for and availability of water.
- The proposed allocation schedule is published for comment by all interested and affected persons.
- The objections and comments must be considered, where after a preliminary allocation schedule is prepared, with the right to appeal to the Water Tribunal by those whose application or claims were unsuccessful.
- The final allocation schedule is published in the Government Gazette.

<u>Accelerated Reform of Water Use Allocations:</u> Apparently due to the slow progress made with compulsory licensing and political demands to urgently address the remaining inequities, a "Framework for Water Allocation Reform" was published (DWAF, 2006a: 4-8). It is again emphasized that change in the way water is allocated is critical to achieve equitable access and benefits from using water. The purpose is to reduce poverty, improve the nutritional status, stave off the debilitating impacts of HIV/AIDS and promote rural growth and development. Since the process of water reallocation to realize equity is technically demanding and legally contentious, participation by all stakeholders is vital. It is acknowledged that water allocation reform is founded on water resource management but is profoundly a social, political, economic and legal process. The important role of water allocation to support economic development will increase as water becomes more limiting. The water allocation process must therefore not only aim at providing water for subsistence farming or for sustaining basic livelihoods, but start a development path of commercial and competitive water use in support of broad based black economic empowerment. It is stated repeatedly that water allocation reform specifically aims to replace existing lawful water use rights with water licenses under the NWA via compulsory

licensing. In this regard a set of eight guidelines are specified which provide benchmarks against which water allocation processes must be tested (DWAF, 2006a: 9-12). Of particular significance is guideline 5: “The water allocation process must be undertaken in a fair, reasonable and consistent manner and existing lawful uses will not be arbitrarily curtailed”. Different approaches towards implementation are given (DWAF, 2006a: 13-19), where (a) the allocatable water is sufficient to meet the needs of applicants and claimants; (b) needs exceed the allocatable water; and (c) allocation in catchments that have been prioritized for compulsory licensing.

Since water rights were linked to land, an unequal allocation of water on private land was caused by racially-based discriminatory legislation and measures on land ownership from 1913 onwards. An ambitious programme of land reform was launched to accomplish restitution of forced dispossession; tenure reform to secure and extend tenure rights because of past discriminatory practices; and redistribution with discretionary grants to acquire land through the market process. The initial target to redistribute 30% of the total commercial agricultural land within five years was not achieved. Up to 2004 only 3.1% of the total commercial agricultural land of 82 million ha in private ownership was approved for transfer and the timescale has now been lengthened to fifteen years. The reasons for the slow progress with reforming landholdings and recommendations for renewed efforts have been extensively discussed and documented. Major emphasis is placed on administrative capability in government departments, sufficient budget allocations, good governance and challenging the acceptability of the market based approach for redistribution (cf. Lahiff, 2003: 85-97; Hall and Ntsebezu, 2007: 2-20).

In relation to water allocation reform the biggest challenge is to synchronize reform programmes in irrigation areas to ensure that beneficiaries hold secure land and water use rights. Agricultural policy measures in connection with financing, marketing, training and extension will also have to be taken to support land and water allocation reform, if the intended transformation is to be successful (Groenewald, 2004: 673-682). Nonetheless, collective action through the political and legal process is essential to reach agreement on the re-apportionment of water use entitlements and the outcome of water allocation reform must be generally accepted as fair by all participants in the process.

Legality of Deprivation of Water Use

The social and political basis for continued attenuation of ownership rights to water is found in the Property clause of the Bill of Rights of the Constitution (RSA, 1996). In Section 25(8) it is stated that no provision in this section may impede the government from taking legislative and other measures to achieve land, water and related reform. The National Water Policy (DWAF, 1997: 7-8) refers to the distinction between expropriation and deprivation. The former is considered to be the “complete removal of an established property right” while the latter “merely limits the extent of use of property”. It is then argued that existing lawful use will only be recognized if it is exercised beneficially and authorizing water use is considered to be a deprivation (DWAF, 1997:15).

The question is whether the encroachment upon existing water use rights by changing riparian rights to licences does in fact amount to an expropriation or a deprivation (Pienaar and Van der Schyff, 2005: 270-277). With reference to case law it is found that deprivation is an infringement on property. Where the government places limitations on the use of property to promote economic development, e.g. through water use licensing to the benefit of all, these will be legitimate if the requirements of Section 25(1) of the Constitution have been met, i.e. the limitations must be in terms of generally applicable legislation that may not be arbitrary. It is argued that the National Water Act complies in both instances and that curtailment of exclusive individual use rights to promote sustainable development in the public interest is indeed a constitutionally tenable deprivation. Although no expropriation occurs, i.e. taking of property without consent of the owner which now rests in the government, individuals may be excessively prejudiced by changing the basis for the allocation of water use rights. If the encroachment leads to financial losses or incalculable damages, it can be considered to be inverse condemnation or constructive expropriation which requires fair compensation.

ECONOMIC AND SOCIAL INTERACTION: MAKING WATER MARKETS WORK

Theoretical Principles

With secure water rights, individual control is exercised over water resources and access is gained to a potential stream of net benefits over time. Therefore investments will be made and agricultural production will be undertaken in response to consumer demand for food. If water rights are transferable, holders of these rights are exposed to the opportunity costs (i.e. foregone best alternative uses) of the current use in agriculture. After valuation of benefits and costs, a process of negotiation between willing buyers and sellers can lead to a transaction, which is an agreement to exchange rights at a price. The different alternatives which each individual identifies determine the level of bargaining power and degree of competition. Essentially this interaction is the functioning of the market process: Trade of water rights is therefore the allocation mechanism according to which apportioned water rights can be voluntary transferred on mutually beneficial terms. The ability to appropriate all benefits from use, lease or sale arrangements of water rights is the incentive to improve private and individual interests. This is the pre-requisite for re-allocation of water rights from lower to higher valued crops within irrigated agriculture or from agriculture to domestic and industrial uses. Thereby it contributes to efficient and flexible use and transfer of rights to water resources and productivity growth under conditions of limited and variable water supply (Backeberg, 1997: 362-364).

All property rights and water rights in particular consist of a bundle of rights (Furubotn and Pejovich, 1974: 3-9) These are the rights to use the resource or asset; the right to appropriate returns from the resource; and the right to change the form or content of the resource to which the right applies. Similarly secure property rights and water rights require that the right should be explicit, exclusive enforceable and transferable (Tietenberg, 1992: 45-47; Paterson, 1989: 48). The efficient operation of markets in water rights requires furthermore that rights are non-attenuated, which means that the water right must meet all four of these necessary conditions. This can be achieved only if the form of entitlement enables in principle “an exhaustive partitioning of the resource among title holders” (Paterson, 1989). In other words, the sum of individual lawful claims to water in the catchment management area must equal the sum of apportionable physical water resources available in the catchment. Only under these circumstances does a basis exist for efficient transactions in the entitlements to water. A theoretically innovative approach to realize this in practice is through capacity sharing (CS) of inflow, storage and release of water between all uses and also between users in irrigation (Dudley and Musgrave, 1988: 649-658; Paterson, 1989: 49-54; Dudley, 1990: 79-90).

At this stage two issues must be raised: First, both in the previous and current political economy of water allocation there were eventually no property rights to water but only use rights (It must be assumed that this includes usufructuary rights or the right to retain the benefit obtained from using water). The absence of ownership means that for all practical purposes final control is exercised not by the holders of water use rights but by the bureaucracy that manages water (cf. Pinchot, 1994: 140-141). Second, keeping this attenuation of water rights in mind, the process of reserve determination and compulsory licensing should lead to a complete partitioning of water resources for instream flow and beneficial use. Furthermore, a market process in water use rights can function if the water use licenses are explicit, exclusive, enforceable and transferable (see paragraph on "Land and water allocation reform" above and paragraph on "Water conservation and demand management" below).

Water Conservation and Demand Management

As part of the implementation of the NWRS (DWAF, 2004: 42-45) various interventions are considered to reconcile demand with supply. These include the following:

- Demand management – implementing cost recovery through consumer tariffs and user charges to influence the behaviour of water users and to install technologies which reduce waste and losses of water such as undetected leakages.
- Resource management – regulation of streamflow through storage; control of abstractions and releases; and assessment of the groundwater resource at specific localities.
- Re-use of water – recycling of return flows and treatment of water.
- Control of alien invasive vegetation – clearing of invading alien vegetation and controlling the spread of such vegetation to increase surface runoff.
- Re-allocation of water – enable gradual transfers between use sectors with differential benefits through compulsory licencing, supported by water demand management and trading of water use authorizations.

It is specifically stated that the NWA (1998) does not make provision for water conservation and demand management (WC&DM) but that the definition of conservation makes these measures an essential component of water resource management (DWAF, 2004: 78-80). WC&DM "relates to the efficient and effective use of water and the minimization of loss and wastage of water". However, water demand management is not only about reducing water use. Water users must understand the economic value of water as a scarce resource; and respond to incentives to save water which is then available for allocation to other uses. Sustained reduced consumption of water can lead to postponement of new capital infrastructure and delay increases in the cost of water supply. Finally, demand management can improve the financial independence of organizations such as water user associations (WUA) by balancing the budget through increased revenue collection and reduced unaccounted water and non-payment by users or consumers.

The WC&DM strategy for agriculture provides a framework for "regulatory support and incentives designed to improve irrigation efficiency …. in order to increase productivity and contribute to reducing income inequalities among people supported by farming activities". A plan of action is envisaged which must present the following strategic outputs:

- appropriate measures that reduce wastage of water
- progressive modernization of water conveyance, distribution and application infrastructure, equipment and methods
- preventative maintenance programmes
- water allocation processes that promote equitable and optimal utilization of water
- generation of sufficient irrigation information which is accessible to all stakeholders
- implementation of water audits from the water source to the end user.

In the case of five of these action points, conditions and regulations for WC&DM for water use sector authorization have been published and are currently being reviewed (DWAF, 2006b: 24-28, 41-44). For irrigation and agricultural water use the emphasis is on five categories: (1) measuring devices and information systems; (2) water audits, accounting and reporting to the responsible authority; (3) water management planning and WC&DM measures; (4) management of return flows; and (5) education and awareness raising.

Regarding the above-mentioned water allocation processes it is necessary to refer to statements on transfer and trading of water use licences: According to the National Water Policy (DWAF, 1997:18, 23) markets or trade in "water use allocations" can be considered as an option in future, but will be subject to varying degrees of control. Transfers of water use authorization (DWAF, 2004: 71-72) are dealt with in terms of Section 25 of the NWA (1998) under two circumstances: First, temporary transfers of water authorized for irrigation are either on the same property for a different use or to another property for the same or a similar use. In general these transfers are for one year only, with the option for extension of a further year, and applications for permission must be submitted to the water management organization that has local jurisdiction. Second, permanent transfers involve one user offering to surrender all or part of an allocation to another prospective user. These types of transfers constitute a trade in water use authorizations which must be preceded by a licence application and are subject to all relevant requirements of the NWA. Permanent transfers must be approved by the responsible authority, may be attached with different conditions and the transfer only becomes effective when the new licence is granted. Both temporary and permanent transfers will only be permitted where the original and new water use are from the same water source. Adequate water and the required infrastructure must make it possible to physically deliver the water at different localities.

Under the part dealing with water pricing, water trading is discussed under the heading of achieving equitable and efficient allocation of water (DWAF, 2004: 89). Three points must be highlighted: (a) trade in water use entitlements can promote the shift from lower to higher value uses but are always subject to a balancing of the public interest with the private interest of the water users participating in the trade; (b) the quantity, quality and assurance of supply of the authorized water use which is traded across water use sectors will be carefully considered before permission is granted; (c) regulations will be introduced which specify the conditions of trade, but over the interim period applications must be made in terms of provisions of the NWA.

Markets in Water Use Rights

Legal transfers of water use rights were possible between riparian land owners subject to jurisdiction of water courts and provisions were made in the Water Act of 1956 for transfers subject to ministerial approval. However, until 1992 the official public policy was that transfers had to follow a legislative process and market trades were not considered as a policy option. This changed with a delegation of authority to permit transfers to a regional level and acceptance of an internal policy for this purpose in 1993. The pragmatic implementation of this policy led to official recording of transfers through market trades of water use rights in certain river catchment areas. These trades were apparently activated by a combination of water shortages due to a severely dry season in 1994/95; financial pressures due the high fixed costs (amongst others by levying water charges on farmers who were allocated water use rights but were not irrigating); and opportunities for expansion with more profitable alternative crop choices (Backeberg, 1997: 366; Armitage and Nieuwoudt, 1999: 53; Bate, Tren and Mooney, 1999: 28-30).

Evidence of the Current Performance of Water Markets: Studies have been undertaken to empirically investigate the nature of these market trades in irrigation areas of two river catchments, namely the Orange River in the Northern Cape Province (Armitage and Nieuwoudt, 1999: 83-101; Armitage *et al.,* 1999: 301-310) and the Crocodile River in Mpumalanga Province (Bate, Tren and Mooney, 1999: 31-42). In both areas trades were from upper to lower regions and there were more sellers (lessees) than buyers (lessors). Only permanent trades were recorded in the Orange River areas while both permanent and temporary trades took place in the Crocodile River areas. The average trade price for water use rights was calculated at 22.53 c/m^3 (1996 basis) and 18.75 c/m^3 (1995 basis) respectively (1US$=7ZAR).

Buyers had larger farms with more irrigated land. Additional water was demanded to expand production of table grapes and sugar cane in the two respective areas and to obtain a higher assurance of supply. Since water supply is more variable in the Crocodile River, higher assurance was the most important reason for buyers to engage in trade. Sellers mostly had not used the water allocated to them. For both areas water was therefore sold by non-users to users, indicating productive use. The most significant variable distinguishing between buyers and sellers as well as buyers and non-buyers in the Orange River is whether farmers grew table grapes – indicating a shift to higher value use; and the expected return per unit of water applied – indicating a shift to most efficient users of water. The unit of measurement of water was completely specified (a water allocation of 15 000 m^3 per ha), with farmer to farmer transfers there was certainty in what was traded and predictable outcomes of transactions. Officials of the regional office of the Department of Water Affairs and Forestry and the local Irrigation Boards performed a function of supervising and recording the transactions as well as providing market information on potential buyers and sellers.

During a follow-up study (Gillitt and Nieuwoudt, 2004; Gillitt *et al.* 2005a: 374-381; 2005b: 393-399) it was found that farmers in both irrigation areas are risk averse. These farmers expect to invest less in future and results indicate that this includes mainly farmers who consider water licences as being not secure. For the Orange River the available results confirm a transfer of water use from relatively lower to relatively higher value crops and from less efficient to more efficient irrigation technology. For the Crocodile River it was found that transfers can be explained better by lower production and financial risks than by higher income per unit of water. In these last mentioned irrigation areas approval of requests for transfers have been delayed because of uncertainty regarding the availability of allocated water.

<u>Proposals to Improve the Performance of Water Markets:</u> The functioning of water markets under the NWA in South Africa has been reviewed (Conningarth Economists, 2004: 73-81). After an initial increase in 1999, the number of transactions appears to have stabilized at 200 per year up to 2003. In this period most transactions occurred in different irrigation areas of the Orange River. Based on the requirements for implementation of trading in terms of the NWRS and the available evidence of the experience gained so far, efforts to improve the performance of markets, or conversely to reduce the chance of market failure, should focus on three broad issues:

(1) <u>Improving the complete specification of water use entitlements:</u> Probably the biggest challenge, particularly for river catchments which are under stress, is to finalise reserve determinations and to reconcile licence applications for use of water with available flows and stocks of water resources. This is more urgent in cases where *ad hoc* licence applications have to be processed to transfer unused water. The water use entitlement should precisely quantify the volume and reliability for a particular user and location. Other users should be excludable and all benefits and costs from use should accrue to the holder of the entitlement. The entitlement should prevent encroachment of use and arbitrary curtailment or involuntary confiscation. The use entitlement should be voluntarily transferable to the mutual benefit of title holders. The finding of case studies is that the insecurity of renewable water licences has to be corrected and that information must be provided to reduce uncertainties in the policy and legal environment (Backeberg, 2006: 8-10). The only sustainable way forward to achieve this is a comprehensive assessment of available water resources and existing use of these resources from the source to the end user. In this regard the theoretical requirements and practical application of capacity sharing (CS) as an alternative institutional arrangement has been investigated for irrigation areas in the middle Orange River (Viljoen, *et al.,* 2004: 67-87, 171-231). As is the case in the lower Orange River, it was shown that secure long-term water use entitlements are essential. Decentralisation of decision-making powers to catchment management agencies (CMA's) and WUA's for re-allocation with transfers is preferred. Through modeling it was demonstrated that implementation of CS can lead to optimal and efficient allocation of water use rights, if withdrawal or release of water for irrigation from storage dams is managed by holders of capacity shares. The approach of fractional water allocation (FWA) of flows and CS of storage for all uses and users has been tested further in the process of compulsory licencing in the Mhlatuze catchment in KwaZulu-Natal province (Pott *et al.* 2005: 23-34). This institutional arrangement meets the requirement of "full partitioning of water resources" between uses. It means that incentives exist for users to improve the efficiency of use and transfers through trade of water use entitlements. Computer programmes are available and have been refined to provide decision-support to holders of entitlements (farmers) and managers (officials) in WUA's or

regional offices of DWAF. Specifications are provided for water measuring, accounting and auditing which comply with the condition for WC&DM. However, it must be noted that no market trading has up to now been developed in these irrigation areas (Nieuwoudt and Armitage, 2004: 5-8). This can be attributed to uncertainty created by the compulsory licencing process, the desire to maintain the present assurance of supply and no profitable alternative crops.

(2) Lowering transaction costs: The main emphasis should be on streamlining administrative procedures to receive, process and approve or refuse applications for transfer of water use authorization (Döckel, 2006: 48-52). This includes addressing the technical and managerial competence of staff; the degree of centralization or decentralization of the responsible authority; and the time it takes to process applications. Matters are complicated further by the fact that organizations such as CMA's and WUA's have not been established in all water management areas and irrigation schemes and there is a high staff turn-over in the public sector, affecting the regional and head office of DWAF. Apart from the time factor, transactions will be further facilitated by reducing the costs of contracting and ensuring that infrastructure are provided to deliver the water (Thompson 2006: 517-521). Opportunities arise for hydrological consultants, legal and financial advisors, valuators and brokers in the private sector to provide information and conclude transactions (Saliba and Bush, 1987: 51). Bargaining and negotiations over the volume and price of water use transfers must nonetheless be without undue interference. Clear guidelines must be provided to approve or prohibit transfers and a register of legally sanctioned entitlements must be maintained (Backeberg, 1994: 233-234).

(3) Reducing third-party impacts: A range of economic, social and ecological external impacts must be considered before approving transfers (Döckel, 2006, Thompson, 2006). Examples are black smallholder farmers selling entitlements to white commercial farmers for short-term gain; large numbers of farmers selling water use entitlements to generate cash but with negative long-term consequences for the indirectly dependent community members on an irrigation scheme; changes in the instream flow or quality of water and possible detrimental effects on bio-diversity of river systems. In all cases comprehensive and accurate information is required. This will become even more important when inter-sectoral transfers from irrigation to domestic or industrial uses will start to happen.

Building Trust Between Cultures

The fundamental requirement for effective interaction between people in the market process to transfer and trade water use entitlements is trust between the persons involved in the transaction (Backeberg, 2003: 164-167; Thompson, 2006: 521). This trust relationship between social groups is strained, firstly because collective political action for water allocation reform is mainly compulsory licensing with transfers from white to black farmers, while individual market action for transfer of water use rights is mainly between white farmers, with claims of enrichment on both sides. Secondly, farmers as members of society operate within different cultures and there is a need to understand and appreciate the values, attitudes, habits, beliefs and behaviour of these cultures. According to Robins (2005: 2-7) the challenges for social transformation are to be found in "specific, concrete realities and everyday struggles, negotiations and pragmatic compromises" … "Recognising rights does not necessarily mean the denial or dismissal of cultural recognition claims”. Given the historical discrimination based on racial and ethnic identities, ‘culture talk’ is still a sensitive subject. Nonetheless, the fact is that different cultures cause tension between negotiation styles based on liberal democratic principles and the dictates of traditional authorities.

This means that culture is part of the interaction between people in society; ethnicity is the expression of culture in a broader African and European social identity; and “organizational rules” are the explicitly accepted modes of behaviour. While all South Africans have an African identity, people are living in a multi-cultural society (Khoza, 2005: 106-110). One manifestation of this cultural diversity becomes clear when African communalism is compared with European (Western) individualism (Van der Walt, 2003: 133).

African communalism	European individualism
Interdependence	Independence
Group assurance	Personal gratification
Co-operation and harmony	Conflict and competition
Affiliation	Ownership
Shared duties	Individual rights

These differences should not be divisive but enrich society. It does however require a conscious effort by all members of society to recognize and respect cultural differences. This will be particularly important in the process that is followed to negotiate a business transaction. It is most relevant for the transfer and trade of water use entitlements between white farmers on freehold land and black farmers on communal land.

Change in the sense of transformation will require a paradigm shift by all participants in the transaction (Esterhuyse, 2004: 190-193). The moral perspective is transforming the pattern of behaviour in a commonly shared, open and non-racial economy and society. The strategic perspective is equitable access to resources and economic opportunities. This goes beyond black economic empowerment through ownership of resources, by effectively addressing socio-economic inequalities through dynamic people development and economic growth.

CONCLUSION

The problem of conflict over allocation of water resources for irrigation in the post-constitutional democratic era in South Africa has to be solved by a combination of political/legal and economic/market processes. Collective action is necessary to correct unequal rights and access to water resources. This has been achieved by constitutional means and through the National Water Act (NWA). With implementation of the National Water Resource Strategy compulsory licencing of existing lawful use is under way to establish a fair apportionment of water use entitlements between current and prospective users. Approximately ten years after inauguration of the new political and legal dispensation, water allocation reform is in the early stages. It will require more human, financial and time resources to complete in all water management areas than was initially anticipated.

In this period of transition the challenge will be to improve agricultural and rural economic growth. With water resources allocated for irrigation classified as a merit resource (Randall, 1983: 134-138), it will require the involvement of both private enterprise and government authority. The absolute minimum requirement for water allocation reform to the benefit of black and white farmers in irrigated agriculture is that there must be physical, tenure and legal security of water use. Under these circumstances investment and production decisions will be made to produce food according to market demands. However, improvements in the design of water institutions and the process of water use authorizations are essential. Starting with the present definition of water use in the NWA, the complete specification of water use entitlements must be done at the source. The concepts of capacity sharing developed and implemented in Australia and Zimbabwe (Viljoen, *et al.*, 2004; Pott *et al.*, 2005) are a good guide to ensure that entitlements are explicit, exclusive, enforceable and transferable. On this basis efficient use and trade of entitlements through market processes can be promoted. Holders of water use entitlements have clear rights and obligations; exercise freedom of choice within generally approved rules; and accepts responsibility for their actions. In such a market driven agricultural economy new wealth is created through individual enterprise.

Since the water market is a regulated market, government authorities perform an important function but must be responsive to user demands. Changes are therefore also required in the way water resources are managed and market processes are facilitated. This can be done by following transparent administrative procedures when evaluating transfers, providing management advice, reducing transaction costs and protecting third-party interests. These functions will become more important when inter-sectoral transfers and trades of water use authorisation are considered. In all social and economic relationships between people the reality of a culturally diverse society also means that tolerance and mutual respect must continually be encouraged and practiced. Every member of society has the right to participate but also the obligation to make a mind-set change and work towards establishing trust and social harmony. Consequently the strategic objective is to invest in human capital in order to develop and use water resources for socio-economic transformation and economic prosperity in irrigated agriculture (Backeberg, 2006: 9-10).

In summary the experience with management of water allocation is that the "playing field" must be leveled through the political process. The "rules of the game" must be clarified by establishing legitimate water institutions. Incentives then exist to enable participation by all "players" to utilize opportunities and create wealth through individual entrepreneurship. The most effective way to achieve this is to encourage a competitive "game" by facilitating a market process in water entitlements.

REFERENCES

Armitage, R.M. and Nieuwoudt, W.L. (1999). *An economic analysis of surface irrigation water rights transfers in selected areas of South Africa.* Report No. 870/1/99, Water Research Commission.

Armitage, R.M., Nieuwoudt, W.L. and Backeberg, G.R. (1999). Establishing tradable water rights: Case studies of two irrigation districts in South Africa. *WaterSA,* Vol. 25, No. 3.

Backeberg, G.R. (1994). A political economy approach to adjustment of water institutions in irrigated agriculture. *Agrekon,* Vol. 33, No. 4. (in Afrikaans).

Backeberg, G.R. (1995). *Towards a market in water rights: A pragmatic institutional economic approach.* Discussion paper submitted to the Department of Water Affairs and Forestry. Land and Agriculture Policy Centre: Johannesburg.

Backeberg, G.R. (1996a). Constitutional change and natural resource policy reform in South Africa: conducive or obstructive to sustainable economic growth of agriculture? *Agrekon,* Vol.35, No. 4.

Backeberg, G.R. (1996b). The challenge of irrigation policy reform in the mature water economy of South Africa. *Security and Sustainability in a Mature Water Economy: A Global Perspective.* Pigram, J.J. (eds). Centre for Water Policy Research, University of New England. Water and Resource Economics Consortium, Proceedings of an International Workshop. University of Melbourne: Melbourne.

Backeberg, G.R. (1997). Water institutions, markets and decentralized resource management: prospects for innovative policy reforms in irrigated agriculture. *Agrekon,* Vol.36, No4.

Backeberg, G.R. (2002). Evolution of water rights in South Africa. In Bate, R. and Tren, R. *The cost of free water: The global problem of water misallocation and the case of South Africa.* The Free Market Foundation, Johannesburg.

Backeberg, G.R. (2003). Water usage and irrigation policy. In Nieuwoudt, L. and Groenewald, J. (eds). *The Challenge of Change: Agriculture, Land and the South African Economy*. University of Natal Press, Pietermaritzburg.

Backeberg, G.R. (2005). Water institutional reforms in South Africa. *Water Policy,* Vol. 7, No. 1.

Backeberg, G.R. (2006). Reform of user charges, market pricing and management of water: problem or opportunity for irrigated agriculture? *Irrigation and Drainage,* Vol. 55, No.1 . John Wiley & Sons Ltd.

Backeberg, G.R. and Odendaal, P.E. (1998). Water for agriculture: a future perspective. Proceedings of the 39th Ordinary General Meeting of the Fertilizer Society of South Africa (FSSA). 24 April 1998. Sun City Hotel. Pilansberg. *FSSA Journal*. Pretoria.

Bate, R., Tren, R. and Mooney, L. (1999). *An econometric and institutional economic analysis of water use in the Crocodile River Catchment, Mpumalanga Province, South Africa.* Report No. 855/1/99. Water Research Commission, Pretoria.

Bromley, D.W. (1989). *Economic Interests and Institutions: The Conceptual Foundations of Public Policy*. Basil Blackwell, New York and London.

Ciriacy-Wantrup, S.V. (1985) Water policy and economic optimizing: Some conceptual problems in water research. In Bishop, R.C. and Anderson, S.O. (eds) *Natural Resource Economics: Selected Papers*, Westview Press Inc., Boulder, Colorado.

Conningarth Economists. (2004). *The facilitation of trade in water use entitlements by the National Water Act in South Africa*. Report No. 1297/1/04, Water Research Commission, Pretoria.

De Coning, C. and Sherwill, T. (2004). *An assessment of the water policy process in South Africa (1994-2003).* Report No. TT232/04, Water Research Commission, Pretoria.

Department of Water Affairs and Forestry (DWAF). (1996). *Water Law Principles*. Discussion document, Pretoria.

Department of Water Affairs and Forestry. (1997). *White Paper on a National Water Policy for South Africa,* Pretoria.

Department of Water Affairs and Forestry. (2004). *National Water Resource Strategy* (First Edition), Pretoria.

Department of Water Affairs and Forestry. (2006a). *Guidelines for Water Allocation in South Africa: A Framework for Water Allocation Reform,* (Draft 2.2), Directorate: Water Allocation, Pretoria.

Department of Water Affairs and Forestry. (2006b). *Water Conservation and Water Demand Management Conditions: Use of Water for Domestic, Agriculture and Industrial Sectors,* (Final report version 1.0), Directorate: Water Use Efficiency, Pretoria.

Döckel, J.A. (2006). The possibility of trade in water use entitlements in South Africa under the National Water Act of 1998, In Perret, S., Farolfi, S. and Hassan, R. *Water Governance for Sustainable Development: Approaches and Lessons from Developing and Transitional Countries.* Earthscan.

Dudley, N. (1990). Alternative institutional arrangements for water supply probabilities and transfers. In Pigram, J.J., Hooper, B.P. (eds).*Transferability of Water Entitlements: Proceedings of an International Seminar and Workshop.* The Centre for Water Policy Research. University of New England, Armidale.

Dudley, N.J. and Musgrave, W.F. (1988). Capacity sharing of water reservoirs, *Water Resources Research*, Vol. 24, No. 5.

Esterhuyse, W. (2004). Recovering the soul of the South African nation. In *South Africa at 10: Perspectives by political, business and civil leaders,* World Economic Forum, Human and Rosseau, Cape Town and Pretoria.

Furubotn, E.G. and Pejovich, S. (1974). *The Economics of Property Rights.* Ballinger Publishing Company, Cambridge, Massachusetts.

Gillitt, C.G. and Nieuwoudt, W.L. (2004). Water Markets in Irrigation Areas of the Lower Orange and Crocodile Rivers of South Africa, Report No. KV160/04, Water Research Commission.

Gillitt, C.G., Nieuwoudt, W.L. and Backeberg, G.R. (2005a). Water markets in the lower Orange River catchment of South Africa, *Agrekon,* Vol. 44, No. 3.

Gillitt, C.G., Nieuwoudt, W.L. and Backeberg, G.R. (2005a). Water marketing in the Crocodile River, South Africa, *Agrekon*, Vol. 44, No. 3.

Goldblatt, M. and Davies, G. (2002). Water, energy and sustainable economic development in South Africa, *Development Southern Africa*, Vol. 19, No. 3.

Groenewald, J.A. (2004). Conditions for successful land reform in Africa, *South African Journal of Economic Management Science*, Vol. 7, No. 4. Juta & Co.

Hall, R and Ntsebeza, L. (2007). Introduction to *The Land Question in South Africa: The Challenge of Transformation and Redistribution,* Ntsebeza, L. and Hall, R. (eds), HSRC Press, Cape Town.

Hofstätter, S. (2007). Communal land: a breeding ground for corruption, *Farmer's Weekly*, 2 February 2007.

Jacobs, N. (2003). *Environment, Power and Injustice: A South African History.* Cambridge University Press.

Khoza, R.J. (2006). *Let Africa Lead: African Transformational Leadership for 21st Century Business.* Vezubuntu Publishing (Pty) Ltd, Sunninghill.

Lahiff, E. (2003). Land policies and practices, In Reed, D. and De Wit, M. (eds), *Towards a Just South Africa: The Political Economy of Natural Resource Wealth.* WWF Macroeconomics Programme Office, Washington and CSIR – Environmentek, Pretoria.

MacKay, H. (2003). Water policies and practices, In Reed, D. and De Wit, M. (eds), *Towards a Just South Africa: The Political Economy of Natural Resource Wealth.* WWF Macroeconomics Programme Office, Washington and CSIR – Environmentek, Pretoria.

Nanda, V.P. (ed). (1977). *Water Needs for the Future: Political, Economic, Legal and Technological Issues in a National and International Framework.* Westview Special Studies in Natural Resources and Energy Management, Westview Press: Boulder, Colorado.

Nieuwoudt, W.L. and Armitage, R.M. (2004). Water market transfers in South Africa: Two case studies, *Water Resources Research,* Vol. 40.

Nieuwoudt, L. and Groenewald, J. (eds). (2003). *The Challenge of Change: Agriculture, Land and the South African Economy.* University of Natal Press. Pietermaritzburg

Paterson, J. (1989). Rationalised law and well-defined water rights for improved water resource management. *Renewable Natural Resources: Economic Incentives for Improved Management.* Organisation for Economic Cooperation and Development, Paris.

Pienaar, G.J. and Van der Schyff, E. (2005). The history, development and allocation of water rights in South Africa, In Tempelhoff, J.W.N. (ed). *African Water Histories: Transdisciplinary Discources,* Corals Publishers.

Pinchot, G. and E. (1994). *The End of Bureaucracy and the Rise of the Intelligent Organisation.* Berret-Koehler Publishers, San Francisco.

Pott, A., Hallowes, J., Mtshali, S., Mbokazi, S., Van Rooyen, M., Clulow, A. and Everson, C. (2005). *The Development of a Computerized System for Auditing Real Time or Historical Water Use from Large Reservoirs in Order to Promote the Efficiency of Water Use,* Report No. 1300/1/05, Water Research Commission, Pretoria.

Randall, A. (1983). The problem of market failure. *Natural Resources Journal,* Vol. 23.

Reed, D. (2001). *Economic Change, Governance and Natural Resource Wealth: The Political Economy of Change in Southern Africa,* Earthscan Publications Ltd.

Republic of South Africa (RSA). (1996). The Constitution of South Africa (Act No. 108 of 1996), Cape Town.

Republic of South Africa. (1998). The National Water Act (Act No. 36 of 1998), Government Gazette.

Robins, S.L. (ed). (2005). *Limits to Liberation after Apartheid: Citizenship, Governance and Culture,* James Currey, Oxford; Ohio University Press, Athens; David Philip, Cape Town.

Saliba, B.C. and Bush, D.B. (1987). *Water Markets in Theory and Practice: Market Transfers, Water Values, and Public Policy.* Studies in Water Policy and Management No 12. Westview Press: Boulder and London.

Schmid, A.A. (1972). Analytical institutional economics: Challenging problems in the economics of resources for a new environment. *American Journal of Agricultural Economics*, Vol. 54, No. 5.

Schmid, A.A. (1978). *Property, Power and Public Choice: An Inquiry into Law and Economics.* Praeger Publishers, New York and London.

Thompson, H. (2006). *Water Law: A Practical Approach to Resource Management and the Provision of Services*, Juta and Company Ltd, Cape Town.

Tietenberg, T. (1992). *Environmental and Natural Resource Economics.* (Third Edition). New York, Harper Collins Publishers Inc.

Van Averbeke, W. and Mohamed, S.S. (2006). *Smallholder Irrigation Schemes in South Africa: Past, Present and Future*, Keynote Paper, Second Symposium of the South African National Committee on Irrigation and Drainage (SANCID), 14 November 2006, Swadini Aventura Resort, Hoedspruit, www.SANCID.org.za.

Van der Walt, B.J. (2003). *Understanding and Rebuilding Africa: From Desperation Today to Expectation for Tomorrow*. The Institute for Contemporary Christianity in Africa, Potchefstroom.

Viljoen, M.F., Dudley, N.J., Gakpo, E.F.Y. and Mahlaha, J.M. (2004). *Effective local management of water resources with reference to the middle Orange River*. Report No. 1134/1/04. Water Research Commission, Pretoria.

Weatherford, G.D. (1982). Institutional framework for agricultural water conservation and reallocation in the West: A policy analysis. In Weatherford, G.D., Brown, L., Ingram, H. and Mann, D. (ed). *Water and Agriculture in the Western US: Conservation, Reallocation and Markets.* Studies in Water Policy and Management, No. 2, Westview Press, Boulder Colorado.

THE FORMULATION OF THE SACRAMENTO VALLEY INTEGRATED REGIONAL WATER MANAGEMENT PLAN: A FOUNDATION FOR CONTINUED REGIONAL COORDINATION

Mark T. Oliver[1]
David J. Guy[2]

ABSTRACT

Historically, competing agricultural, environmental, and urban demands present serious water management challenges within the Sacramento Valley. In meeting these challenges, water users, conservation organizations and local governments across the Sacramento Valley continue to build on the foundational efforts initiated during the last prolonged drought in the early 1990s. These early efforts provided the initial working relationships that have promoted the sharing of ideas, regional thinking, and collective planning across the Sacramento Valley. Building on these various sub-regional efforts and relationships, which have been and continue to be supported by state and federal agency funding and participation, the diverse parties in the Sacramento Valley continue to proactively implement and evaluate the means for improved water management. These efforts to date have resulted in the implementation of numerous projects to improve the management of the valley's water and natural resources, the development of a number of sub-regional plans, and the recent completion of the Sacramento Valley Integrated Regional Water Management Plan (IRWMP). The IRWMP is a living and dynamic document that will be used as a basis to further explore opportunities to develop, plan, monitor, and implement programs and projects across the valley. It is anticipated that this integrated approach will continue to improve ecosystem and fishery resources, water quality, and water supply reliability throughout the region.

INTRODUCTION AND BACKGROUND

Regional water management planning in the Sacramento Valley (Valley) began in 1991 when water leaders throughout the region formed the Northern California Water Association (NCWA). During this time, the valley and the state were in the midst of prolonged drought, which began in 1988 and extended to 1994. While the 1976-77 drought was more intense in nature, this longer drought revealed certain vulnerabilities in California water management that led to important changes, many of which dominate the water landscape today. It was during this time that California Governor Pete Wilson, rather than declare an emergency, created the Drought Water Bank (largely focused on the Sacramento Valley) to help meet water supplies in California. The federal and state endangered species acts also came to a head in their respective courts regarding diversions off the Sacramento River; and Congress, the State Legislature and counties took

---

[1] Mark T. Oliver is a Water Resources/Environmental Program Manager with CH2M HILL in Redding, CA. (see www.ch2m.com)

[2] David J. Guy was the Executive Director of the Northern California Water Association (NCWA) in Sacramento, CA at the time this article was prepared. (see www.norcalwater.org) He is currently the Chief Executive Officer for the Yosemite Association in El Portal, CA. (see www.yosemite.org). Todd Manley and Tina Lunt provided valuable assistance in the preparation of this article and have helped develop many of the programs described herein.

various actions to respond to the drought. Congress also passed the Central Valley Project Improvement Act (CVPIA) in 1992, which altered the way the Central Valley Project (CVP) was operated on the west side of the Valley. These actions led to fundamental changes in the way the Sacramento Valley viewed and thereafter tackled water management.

What ensued was a number of actions, including one of the most aggressive fish passage improvement programs in the world, where water districts, companies and individuals installed fish screens, siphons, fish ladders and made habitat improvements. These improvements have led to important trends for the recovery of salmon and other fish in the region, while helping to assure water for farms, waterfowl and other terrestrial species. Additionally, during this time a large group of senior Sacramento River water right holders with water right settlement contracts with the Bureau of Reclamation developed a Basin-Wide Water Management Plan and recently completed a Regional Water Management Plan to promote regional management. This, in turn, provided a framework for the Sacramento Valley Water Management Agreement (SVWMA) (see www.norcalwater.org) and the Sacramento Valley Water Quality Coalition (composed primarily of individual farmers and wetland managers) which represent new and creative ways to protect water rights and quality in the Sacramento Valley, while helping to meet water supply and quality needs in the Bay-Delta and areas that depend on the Bay-Delta. Most notably, these programs and many similar efforts in the Sacramento Valley began to coalesce as an integrated water management program built on common interests and respecting local autonomy in the region.

THE FIRST MAJOR STEPS TOWARD REGIONAL MANAGEMENT: THE SACRAMENTO RIVER BASINWIDE WATER MANAGEMENT AND REGIONAL WATER MANAGEMENT PLAN

The Sacramento River Basinwide Water Management Plan (BWMP) was prepared by the Sacramento River Settlement Contractors (SRSC) with assistance and input from the California Department of Water Resources (DWR) and the Bureau of Reclamation (Reclamation). At this time, the negotiations of the Sacramento River Water Right Settlement Contracts with Reclamation were beginning. The BWMP was prepared to meet the requirements of the January 1997 Memorandum of Understanding between the Settlement Contractors and the United States of America for the Preparation of Data in Aid of the Renewal of Settlement Contracts.

The BWMP process was a successful, cooperative effort among the SRSCs, Reclamation, and DWR, as evidenced by the following:

- As an important precursor activity to the contract renewal process, the BWMP process provided for an open dialogue and increased understanding of the water resources issues facing the Sacramento River Basin, particularly the lands served by the SRSCs.
- The BWMP process provided a technical forum for addressing the different methodologies of water resources management and the associated technical issues.
- The BWMP process provided the necessary data and background to allow the ultimately successful completion of the contract renewal process.

- The BWMP process provided the framework for the subsequent development of the successful Phase 8 negotiations to the Bay-Delta Water Rights Hearings (the Sacramento Valley Water Management Agreement [SVWMA]; see below under “The Sacramento Valley Water Management Agreement”). The foundation of regional cooperation, coupled with the dialogue and understanding that was established among the major project participants, provided a backdrop for the successful development and negotiation of the Phase 8 settlement.

The BWMP process has been a lengthy endeavor culminating in 2004 after more than five years of discussion, coordination, data, and project development. Significantly, the Sacramento River Water Right Settlement Contracts were executed beginning in January 2005. Additionally, the process itself was a key foundational step in the move toward regionalization.

Based on the success of the BWMP, the SRSC and Reclamation worked jointly to develop regional criteria which could be used to establish the adequacy of a regional plan. During the formulation of the plan, the recognition that one water district’s outflow was another district’s supply was reinforced time and time again. This “flow-through” characteristic of the valley had long been known by many of its water users, but has not been well understood by many outside the Valley nor very well documented. This reality, coupled with the benefits of working together toward collectively beneficial solutions, reinforced the benefits of working together. Historically, water districts with contracts with Reclamation have (and continue to do so across the rest of the west) prepared individual plans focused on district-specific management goals and practices. With the development of the Regional Criteria for Evaluating Water Management Plans for the Sacramento River Contractors (Regional Criteria), the SRSC and Reclamation formalized their intent to chart a new course in regional management.

The culmination of the joint SRSC/Reclamation effort was the development of the SRSC Regional Water Management Plan (RWMP), which was adopted by the eight participating water districts and companies in March 2007. The content of the RWMP includes:

- Regional description and resources
- Sub-basin water use and supply
- Regional water measurement program
- Analysis of sub-regional level CALFED Quantifiable Objectives (QOs) and Targeted Benefits (TBs) and actions proposed to meet QOs
- Establishment of monitoring program
- Proposed budget and allocation of cost
- Regional Plan coordination

Contained within the RWMP are a number of proposed projects intended to assist in meeting the CALFED QOs which include meeting specific flow targets related to helping fishery or terrestrial species, many of which were the basis of projects carried forward to assist in meeting the SVWMA as well as included in the SVIRWMP. It is intended that the data and relationships developed in the preparation of the BWMP and RWMP will continue to foster improved water management across the Sacramento Valley.

THE POTENTIAL WATER RIGHTS BATTLE (PHASE 8) LOOMS…

Given the often competing water needs of agriculture, the environment, and urban areas throughout California, pressure to evaluate all potential management options continues to increase. This evaluation has most recently included existing water contracts and beneficial use of water in general. Current forecasts predict continuing statewide water shortages in both average rainfall and drought years. The Central Valley Project (CVP), operated by Reclamation, and State Water Project (SWP), operated by DWR, supply water to agriculture, cities, and wildlife areas throughout the state through extensive reservoir and conveyance systems. CVP and SWP pumping facilities, located in the Delta, export water to regions south and west of the Delta. The Delta is formed by the convergence of the Sacramento, San Joaquin, and other rivers. Forty percent of California's freshwater originally drained through the Delta. The Sacramento River provides approximately 80 percent of the flows to the Delta and is the major source of water for the CVP and SWP (State Water Resources Control Board [SWRCB], 1995). In addition, the Delta is one of the largest ecosystems for fish and wildlife in the U.S. (SWRCB, 1995).

Since the 1960s, SWRCB has been adopting water quality control plans and conditioning the Reclamation and DWR water right permits with requirements to meet objectives, based on these plans, to protect beneficial uses of the Bay-Delta. The adoption of federal Bay-Delta fish and wildlife objectives, established in 1994, increased the tension between California water users and federal regulators with responsibility for protecting Bay-Delta fish. In December 1994, the agencies and stakeholders (including NCWA) signed the "Principles for Agreement on Bay-Delta Standards between the State of California and the Federal Government," known as the Bay-Delta Accord (Accord). A key provision of the Accord was initiation of SWRCB proceedings to develop a new Bay-Delta water quality control plan that would include the protective Bay-Delta standards of the Accord, called "objectives" in the plan. In May 1995, after a series of workshops, SWRCB adopted its most recent Bay-Delta plan, Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (1995 Delta WQCP; SWRCB, 1995). Another key provision of the Accord was the creation of the CALFED Bay-Delta Program to develop a long-term solution to the complex issues related to meeting Bay-Delta ecosystem needs while also assuring future water supply reliability.

In the Accord, DWR and Reclamation agreed to voluntarily meet the 1995 Delta WQCP objectives until a formal water rights decision determining responsibility for the objectives was completed where the "SWRCB will act in compliance with all provisions of law which may be applicable, including the water rights priority system and the statutory protections for areas of origin." The SWRCB implements the water quality objectives through water right decisions that condition the water right permits of water users, such as Reclamation and DWR. In 1997, and as revised in 1998, the SWRCB issued a notice of the water rights hearings to allocate responsibility for meeting the 1995 Delta WQCP. Because of the complexity of the issues, the SWRCB divided the water rights proceedings into eight phases. Phases 1 through 7 of the proceedings addressed responsibilities for meeting standards related to the San Joaquin River; the Suisun Marsh; the Mokelumne, Calaveras, and Cosumnes River watersheds; Delta salinity; Delta CVP and SWP pumping plant operations; and consolidation of certain uses under Reclamation's permits. The proceedings for the first seven phases occurred from July 1998 to July 1999, included approximately 100 interested parties, and resulted in an administrative record of over 129,000 pages (Proposed Statement of Decision, SWRCB Decision-1641 [D-1641] litigation, p.4, Feb. 27, 2003).

Phase 8 of the hearings would have mainly addressed responsibilities of the users along the Sacramento River north of the Bay-Delta, as well as users south of the Bay-Delta, Reclamation, and the DWR for meeting Bay-Delta flow-related standards to protect fish. In Phase 8, it was anticipated that DWR and Reclamation would claim that certain north of Bay-Delta water right holders must cease diversions during certain periods to help meet the Delta standards. In contrast, it was anticipated that north of Bay-Delta water right holders would likely have claimed that SWRCB should not allocate responsibility to them for meeting the Delta standards because their water use does not contribute to Delta water quality problems and they have senior water rights within the watershed. The Phase 8 process would have ultimately determined which entities and individuals (if any) would be responsible to provide water to meet the flow-related water quality standards.

Most parties of the Phase 8 hearing believed that any SWRCB decision on the matter would likely have triggered litigation and judicial review that, with the hearing process, would extend more than 10 years. This belief is supported by review of the time involved in past SWRCB Bay-Delta decisions, such as the 1978 WQCP and Decision-1485 that resulted in an appellate court decision in 1986. The 1986 appellate decision did not resolve key Bay-Delta water quality and water rights issues, and SWRCB began a new water quality process and water rights hearings, which culminated in D-1641. After D-1641 was adopted in 2000, 11 lawsuits were filed challenging D-1641. The legal wrangling still continues as an 185 page appellate decision was issued in 2006.

Throughout the proceedings, SWRCB encouraged participants to resolve their disputes and present settlement agreements to SWRCB, which SWRCB could then consider when issuing its decision (SWRCB, 1995). As a result of this approach, many of the matters addressed in the first seven phases of the hearings were resolved through settlements. The extended process of a water rights hearing and litigation could have undermined progress on other statewide water management initiatives, such as actions under the CALFED Program which were moving forward at that time.

A LANDMARK COOPERATIVE SOLUTION EMERGES: THE SACRAMENTO VALLEY WATER MANAGEMENT AGREEMENT AND SHORT-TERM WORKPLAN

As the specter of a protracted legal battle loomed, water users subject to the potential Phase 8 proceedings caucused to determine how best to develop a solution that would assist in meeting local as well as regional and statewide water quality and supply needs. The concept of making water available through various means, including improving district water systems, conjunctive water management and reservoir releases was explored. It was determined that a workplan would need to be developed to evaluate the potential for such projects throughout the Sacramento Valley to meet local, Bay-Delta, and statewide needs that could be implemented by local proponents utilizing funding provided through public means.

NCWA and the Sacramento River water right holders invited the export water users and the state agencies to the Vizcaya Pavilion in Sacramento on August 28, 2000 to discuss a framework to resolve the Phase 8 proceedings. The parties agreed to a conceptual approach that was ultimately described in “Agreement Regarding Resolution of Phase 8 Issues, Development and Management of Water Supplies, and Binding Commitment to Proceed Pursuant of Specified Terms” (April 3, 2001, and known as the “Stay Agreement”). The Stay Agreement proposed goals and principles to resolve issues of the flow-related standards that would have been argued during Phase 8.

The parties to the Stay Agreement all testified before the SWRCB in support of the process, which according to a long-time SWRCB observer, was the first time parties north and south of the Bay-Delta had ever testified together in a Bay-Delta water rights proceeding. As a result, on April 26, 2001, SWRCB issued Order WR 2001-05, which postponed Phase 8 and allowed for automatic dismissal of the Phase 8 hearing after 18 months in October 2002 (unless Reclamation or the DWR had requested the SWRCB resume Phase 8 because of a breakdown in the settlement process). Under the SWRCB order and as agreed to in the Stay Agreement, Reclamation and the DWR remained committed to meet the flow-related objectives described in Conditions 1 and 2 of D-1641 during the term of the Stay Agreement.

The Basis: The Short-Term Workplan

A key element of the Stay Agreement was that project would be developed by entities in the Sacramento Valley, without interference from the state and federal agencies or the export water users. As such, the parties developed a short-term workplan that included approximately 40 water management projects and evaluations in the Sacramento River upstream watershed that could help provide water for upstream local water use, CVP and SWP water supply needs, and the environment. In October 2002, prior to the automatic dismissal of the Phase 8 hearing, Reclamation and DWR requested that SWRCB extend the dismissal until after the parties of the Stay Agreement could execute the “Short-Term Agreement to Guide Implementation of the Short-Term Water Management Actions to Meet Local Water Supply Needs and to Make Water Available to the SWP and CVP to Assist in Meeting the Requirements of the 1995 Water Quality Control Plan to Resolve Phase 8 Issues” (known as the “Short-Term Settlement Agreement”). The Short-Term Settlement Agreement incorporated the goals and principles of the Stay Agreement; continues the commitment of Reclamation and DWR to meet the D-1641 flow-related standards; and provides for a collaborative process among the parties to develop projects to meet water supply, water quality, and environmental needs in the Sacramento Valley, the Bay-Delta, and throughout California. On January 31, 2003, as a result of SWRCB Order WR 2002-0012, Phase 8 of the Bay-Delta Hearings was dismissed.

As part of the Short-Term Settlement Agreement, a short-term workplan was developed to investigate projects to meet the goals of the Agreement. Short-term projects were defined as projects that could potentially be implemented and provide benefits by within the first two years of the agreement. The Short-Term plan was completed in October 2001.

Process The Short-term Workplan was prepared by the Workplan Development Team (WDT), which was formed to provide the technical expertise needed to evaluate the projects to be included in the workplans. A Management Team (MT) was formed to oversee the efforts of the WDT and provide policy-related input. The WDT included water district, agency, and consultant staff representing both northern California and south-of-Delta export interests with expertise in the areas of project development, engineering, and benefit/impact assessment. The MT consisted of representatives from all signatory parties for the Settlement Agreement, which included representatives of major water districts and companies across the state, as well as Reclamation, DWR, U.S Fish and Wildlife Service, California Department of Fish and Game, and NOAA Fisheries. Numerous meetings and conference calls were held to ensure agreement on approach and content, and to maintain the schedule.

The primary objective of the Short-term Workplan was to evaluate the technical feasibility and potential benefits and costs of projects submitted by willing participants. Project benefits include potential water supply, environmental benefits, and water quality improvements. This “bottom up” approach (i.e., focusing on projects proposed by willing participants) was considered key to the success of any project and the Agreement as a whole.

Solicitation and Identification of Project Proposals The Northern California Water Association solicited proposals for potential projects throughout the Sacramento Valley on May 7, 2001. The solicitation included a questionnaire requesting a project description, potential supply and other benefits, likely beneficiaries, estimated cost, and schedule. Numerous responses were received from up and down the valley, from as far north as Redding to south of Sacramento. Additional projects were identified through discussions with DWR and review of projects submitted for funding available under various state programs (e.g., AB 303).

Detailed technical evaluations were prepared for each project, and approximately 45 projects were eventually included in the Short-term Workplan spread geographically across the Sacramento Valley. These projects were then grouped into following four major categories:

- Surface/Groundwater Planning – monitoring, area wide inventory, or assessment
- System Improvement – canal lining, tailwater recovery, or improved operations
- Water Management – facilities/ programs to use and monitor surface water and groundwater
- Institutional – transfers or regulatory hurdles

Approach The foundation of the Short-term Workplan was represented by the project evaluation technical studies conducted for each of the proposed projects. Short-term projects were defined as those that could be implemented in the next 1 to 2 years and, therefore, included activities and potential supply quantities that were believed to be technically and institutionally feasible. The following set of initial screening criteria were developed to guide the selection and evaluation of projects:

- Projects will assist in meeting the following goals:
- Provide water to meet local and upstream demands
- Improve water quality and supplies outside the region
- Provide environmental benefits
- Provide operational flexibility
- Will result in a minimum of adverse environmental impacts
- Appear to be institutionally feasible
- Appear to be technically feasible
- Could be implemented in water year 2002-03
- No evident environmental permitting fatal flaws according to current knowledge/expert opinion

Evaluations As discussed above, a summary technical evaluation was prepared for approximately 45 projects evaluated by the WDT and MT. The evaluations include the following information:

- Project description
- Estimated expected net and secondary benefits (including environmental)
- Preliminary estimate of quantity of water or nature of other water management benefits
- Preliminary order-of-magnitude construction cost estimates and determination of expected annual costs (operation and maintenance)
- Major environmental issues and benefits
- Project implementation plan, including the requirements of any monitoring necessary to evaluate the performance of the project
- Potential timetable for implementing the project

Results A generally even distribution of project types was proposed across the Valley, with the majority of projects being proposed in the Colusa Sub-basin northwest of Sacramento. Per the Short-term Workplan, it was estimated that the water management projects collectively could yield as much as 185,000 acre-feet of potentially “new” (water not currently available for use during the spring/summer period) water supplies. The system improvement projects were estimated to provide potentially 100,000 acre-feet in benefits, although most of this amount was anticipated to occur in the form of re-routed flows and, therefore, was not generally considered a "new" water supply. Accordingly, these supplies are not additive. In addition, many of the projects were identified to provide the following qualitative benefits:

- Additional water supply
- Changes in timing/availability of supplies
- Improved water quality
- Improved knowledge of groundwater/surface water interaction
- Improved understanding of groundwater resources and aquifer characteristics
- Identification of regulatory/policy constraints and development of mutual solutions (for institutional projects)

Review of each of the projects revealed that differing operations of any given project could conceivably result in differing potential benefits. For example, a proposed project within one sub-basin could be operated to assist in meeting municipal user needs in particular years, or water could instead be transferred out of the sub-basin to meet other needs. Similarly, a project in another sub-basin could be operated to maximize local environmental benefits (e.g., supplement stream flows or support riparian vegetation) or to transfer water to assist in meeting Bay-Delta water quality requirements. The total estimated cost to implement all projects was approximately $90 million (2001 dollars), broken down as follows:

- Water Management–$40 million
- System Improvement–$35 million
- Planning–$15 million

The majority of potential supply benefits were identified in the Colusa Sub-basin, in large part because Colusa Sub-basin had the greatest number of projects being proposed of any sub-basin. Some areas, such as the Sutter Sub-basin located north of Sacramento, contained very few proposed projects because little data exist regarding Sutter's groundwater and surface water resources or constraints (e.g., water quality limitations).

INDIVIDUAL FARMERS AND WETLANDS MANAGERS UNITE: THE SACRAMENTO VALLEY WATER QUALITY COALITION (SVWQC)

The seeds for the Sacramento Valley Water Quality Coalition were planted in 2001 as agricultural and wetlands leaders in the Sacramento Valley recognized the challenges that lay ahead related to managing water quality issues. The California Central Valley Regional Water Quality Control Board (RWQCB) had found the Sacramento and Feather Rivers impaired for diazinon and it was in the process of designating Bay-Delta tributaries and sloughs as toxic hot spots under California law. Additionally, the Legislature, in fall of 1999, passed SB 390 to rescind the existing waiver of waste discharge requirement programs by the end of 2002, including the agricultural waivers.

As agricultural groups around the Central Valley were organizing, Sacramento Valley leaders looked for models to address water quality in a rural setting. The Sacramento Valley had the benefit of the California Rice Commission (CRC) and its Rice Pesticides Program that started in

1986. It is generally recognized that this program had effectively addressed water quality concerns with rice pesticides. Sacramento Valley leaders also had the benefit of the partnerships, most visibly between water users and Ducks Unlimited, that had successfully restored record fish numbers on Butte Creek and others streams in the Central Valley and had helped restore waterfowl populations along the Pacific Flyway. The Valley leaders also worked with and shared ideas with the leaders in the San Joaquin Valley, who were continuing their efforts to manage water quality issues in a different, although closely related environment in the Central Valley. Fortunately, many of the Coalition leaders had participated a decade earlier in developing an agricultural water quality program for California's Central Coast.

The Coalition members explored many types of institutional approaches. For example, the Coalition explored having commodity organizations develop programs like the California Rice Commission, but recognized that, unlike the rice program, which has a fairly unique set of pesticides as a water emergent crop, many of the constituents of concern were spread across various commodities and could not be addressed by a single commodity organization. Although the SWRCB and Regional Board saw water districts and companies as logical entities to manage water quality programs, the Coalition members in the Sacramento Valley made it clear that water districts and companies make water supply decisions, whereas most of the water quality decisions are basically land use decisions made by individual growers and wetlands managers working with their Pest Control Advisors (PCA's) and Agricultural Commissioners. As such, the Coalition members believed that there needed to be a more direct link between water quality concerns and the agronomic decisions.

What emerged was a nested watershed approach where a macro-level watershed group (the Coalition) formed along geographic boundaries that coincide with the RWQCB's Basin Plan. Nested within the Coalition, Subwatershed Groups formed and took actions necessary for their particular area to improve water quality and to meet specific regulatory obligations. In 2003, more than 200 entities in the region committed to this approach and formally joined the Coalition. This approach captures the efficiency and collective spirit provided by a larger macro-watershed group, while keeping the ultimate decisions affecting water quality close to the ground at the local, subwatershed level.

The Coalition's "Regional Plan for Action" (Regional Plan) has served and will continue to serve as the roadmap for the Coalition by describing a watershed approach for the Sacramento Valley. Developed in June 2003, the Regional Plan will continue to help the Coalition implement the SWRCB and RWQCB Strategic Plan by concentrating on entire watersheds rather than focus on specific constituents. The Plan also carries out the SWRCB Watershed Management Initiative, which specifically recognizes the Sacramento River Basin as a management area or "watershed" and the state policy that "encourages regional planning and action for water quality control." (Water Code section 13255(i).)

The Regional Plan has used a scientific approach to conduct water quality sampling and analyses, prepare timely and comprehensive reports, implement and evaluate management practices, and establish effective educational programs. As required by the RWQCB regulations, the first step in the Plan was the development of a Watershed Evaluation Report (WER) and then a detailed Monitoring and Reporting Program Plan (MRPP). The WER is a comprehensive watershed assessment prepared by local agricultural representatives, wetlands managers and natural resource professionals. The WER provides a detailed description of the landscape in each of the ten Coalition subwatershed areas, including cropping patterns, soil quality, water quality issues, management practices implementation, and pesticide use.

The ultimate output of the WER is a drainage prioritization table for each subwatershed. Using the DWR Land-Use Survey Data, the twenty-one county region was divided into nearly 250 geographic areas. The Coalition evaluated raw acreage numbers for orchard, annual and pasture crops respectively in each drainage area and then multiplied these raw acreages by a “weighting factor” with orchards receiving the greatest emphasis and pasture the least. Adding each of these weighted acreages in each subwatershed produced an index that was used as the primary criterion for ranking a drainage area. The Coalition also evaluated diazinon, chlorpyrifos, copper and pyrethroid use in each drainage area and used this data as the second criterion. The third criterion was the existence of impaired waterbodies listed under the so-called 303(d) list. Each subwatershed group then evaluated the ranked drainages in their subwatershed and based upon their local knowledge of the hydrology and current issues, selected monitoring sites for the initial sampling.

In November 2004, the Coalition and ten Subwatershed Groups executed a Memorandum of Agreement (MOA) that defines the respective roles and responsibilities of the Subwatershed Groups, as well as the Northern California Water Association, Ducks Unlimited and the Coalition for Urban Rural Environmental Stewardship, to implement the Regional Plan, including the roles of consultants that will assist in this process. Additionally, the Coalition has signed a Memorandum of Agreement (MOU) with the California Rice Commission to coordinate the respective programs in the Sacramento River Basin. The Coalition is considering partnerships with municipalities and urban areas in the region that are developing stormwater management plans and facing increasingly more stringent effluent limitations.

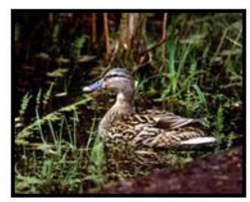
Under the MOA with the Subwatershed Groups, the Coalition in 2005 began fulfilling its water quality monitoring requirements under the RWQCB’s Irrigated Lands Program (ILP). The Coalition annually submits a monitoring plan to the RWQCB; the 2007 monitoring plan, for example, built on both the 2005 and 2006 program and was further tailored to characterize drainage from irrigated lands and managed wetlands in the Sacramento Valley.

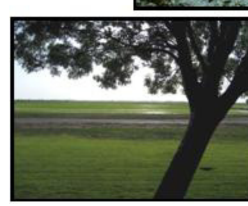
Since the time water quality monitoring was initiated in 2005, two management plans have been submitted to the RWQCB. The first plan addressed Diazinon exceedances in the Sacramento Valley and the second addressed multiple exceedances including boron, conductivity, algal toxicity, and E. coli in Yolo County.

Committed to addressing all exceedances from agriculture, even those not addressed through management plans, the SVWQC on May 10, 2005 sent a letter to the Chairs of the Water Boards outlining a “Management Practices Action Plan” for the Sacramento Valley. Building on both the SVWQC's "Management Practices Action Plan," and the "Regional Plan for Action," the SVWQC submitted a detailed plan on November 14, 2006 that describes an aggressive approach for the SVWQC and its subwatersheds to follow when there are exceedances of water quality objectives formally adopted by the Regional Board.

The refined plan provides a detailed approach the SVWQC and its subwatersheds will take when notifying the affected subwatershed landowners, farm operators and/or wetland managers about the cause(s) of toxicity or exceedance of water quality standards. Depending on the causes of toxicity or exceedances, solutions will include a targeted outreach program with landowners and operators. The outreach program will encourage the adoption of known management practices or modifying the uses of specific farm and wetland inputs to prevent movement of the constituent of concern into the surface water. The SVWQC and its subwatersheds, with the Coalition for Urban/Rural Environmental Stewardship (CURES), have expressed its commitment to work with the Water Boards and their staff to implement this plan to help improve water quality in the Sacramento Valley.

THE REGIONAL EFFORT MATURES: THE SACRAMENTO VALLEY WATER INTEGRATED REGIONAL WATER MANAGEMENT PLAN (IRWMP)





The NCWA Board of Directors in December 2000 adopted "An Integrated Water Supply Management and Water Development Program for the Sacramento Valley" that formally launched the efforts for formal regional planning in the Sacramento Valley. Capitalizing on the momentum achieved through the development of the plans, programs, and projects summarized above, water leaders in the valley initiated the formal planning process in 2005 to prepare a comprehensive regional and integrated water management plan known as the Sacramento Valley Integrated Regional Water Management Plan (IRWMP) for the region. The IRWMP, which was formally adopted under Water Code section 10541 on December 12, 2006, serves as a roadmap for present and future generations for improving water supply reliability for all beneficial uses in the Valley, including water for farms, cities, birds, fish and recreation. In addition, the IRWMP protects the Northern California water users' water rights through formulation and implementation of specific water management strategies that increase the local water supply reliability while improving water quality and quantities in streams, rivers and the Sacramento-San Joaquin River Delta.

The IRWMP provides for the continued development of water resources policies, programs and projects in the Sacramento Valley to address water management challenges arising from the continuing regulatory requirements and the land use changes in the Valley. Implementing the IRWMP will benefit the economy of the Valley by improving water supply reliability and providing for secure and reliable good-quality water for beneficial uses in the region for the years to come.

Planning Approach

Using the lessons learned through the development of the plans and programs summarized above, in addition to numerous other sub-regional efforts including integrated planning programs in the Yuba, Redding/Shasta, Butte, Yolo, and Tehama areas, the fundamental “bottom-up” approach was considered paramount. Accordingly, the IRWMP is not a top-down plan; it is rather a grassroots, bottom-up program composed of many strategies, programs, plans, and partnerships with common objectives and a long-term vision.

This bottom-up approach is reflected in the ‘nested’ planning approach used to prepare this IRWMP. Nested within the IRWMP are subregional integrated regional planning efforts identified above that have been developed to manage water resources in the Valley. These subregional efforts are led by the local agencies, including individual counties, water districts, resource conservation districts, reclamation districts and others, and incorporate planning studies such as groundwater management plans, urban water management plans, communities’ master plans, flood management and drainage studies. These subregional and local efforts have independent utility; yet the ultimate value comes from the combined benefits of the IRWMP that will be larger than the sum of the parts. Therefore, this IRWMP incorporated the subregional planning efforts the use of information gathered by the subregional plans and through close coordination with local entities. It was recognized during the planning process that land use planning decisions of counties and cities are expected to have a significant effect on water resources-related issues such as water supply reliability, water quality conditions, discharge requirements, flood management and stormwater management. Therefore, proper coordination with local government agencies is essential in developing a plan that incorporates land use decisions and addresses water management issues related to future growth within the Valley.

The IRWMP follows more than a decade of cooperative, integrated efforts by local agencies, resource management agencies, and other federal and statewide cooperators. The broad, long-term vision for the region consists of the following:

- **Integration of water resources management and planning processes** in which individual water agencies and water interests in the valley continue concerted coordinated approaches to the planning of multi-beneficiary projects that will achieve the common objectives of all parties.
- **Institutional and political integration** through which institutional and political alliances of water suppliers and government entities formulate, develop, finance, and implement integrated programs for the common benefit of their members and citizens. In addition, building new political alliances and continuing existing ones with entities outside the region will strengthen long-term working relationships and foster long-term, viable water management solutions.
- **Operational integration** providing for the coordinated management and operation of facilities and resources to generate the greatest possible benefit from the available resources.

The long-term vision stated above is a goal that will require years of cooperative efforts between local water purveyors, water interests, and state and federal agencies to achieve. Step-by-step cooperative efforts and implementation programs will be needed to reach this goal. The IRWMP is essentially the most recent step in integrating water resource management and planning processes and providing coordinated implementation of water management strategies in the Valley. Additionally, the participating agencies recognize and support the concept that regional integration will further their ability to manage their operations and collective resources, will increase their water supply reliability, and will provide a framework to improve water management across the region. More importantly, all participating entities are (and must be) assured that they will not lose opportunities to control their own futures nor will they lose their autonomy by participating in a regional integrated water management program. Regional integration does not seek to diminish the individual purveyor's decision-making power or a local government's power and ability to manager its resources. Participating entities will work together in addressing common water management issues on a much larger scale. This vision of integration and regionalization is intended to result in the following:

- Providing opportunities to formulate broad water management objectives at the regional and statewide level.
- Encouraging regional responsibility for the management of the region's resources.
- Pooling regional resources, political wills, and local agencies' talents and expertise to develop creative solutions.
- Creating a powerful voice to protect and enhance regional interests.
- Promoting collaboration and cooperation for regional and subbasin-level initiatives.
- Realization of greater benefits than could have been achieved by agencies acting independently.

Planning Process

Integrated regional water management planning in the Sacramento Valley integrated many projects, plans, and partnerships with common objectives and vision. Partnerships with stakeholders are critical to the success of the IRWMP and its implementation. Numerous public meetings, stakeholder meetings, and interest group meetings were conducted to obtain input and direction. The IRWMP is a living document and will be updated as necessary to reflect changes in the region.

IRWMP Planning Process

- Regional Participants
  – Water Purveyors
  – Counties
  – Cities and Towns
- Partners
  – State/federal agencies
  – Statewide Water Suppliers
- Regional Coordination
  – Foothills
  – Sacramento Metropolitan Area
  – Interested Parties

Participating Agencies

Many of the planning principles for the IRWMP have evolved through years of discussion, negotiations, and agreements between local water interests throughout the Valley. The IRWMP was prepared with guidance and input from water purveyors and other water interests though quarterly meeting presentations and discussions (called managers' meetings). NCWA conducted these meetings to share information, discuss water issues, and receive comments from member agencies. A Regional Water Management Group (RWMG) and other participating entities are responsible for development and implementation of the IRWMP under Water Code section 10537, acting as the Joint Exercise of Powers (JEP).

Plan Objectives and Priorities

The IRWMP objectives were developed through identification of mutual interests among local and regional water users and stakeholders. Extensive coordination and cooperation among sub-regional planning partners was required to ensure consistency with sub-regional objectives. NCWA coordinated the planning process with agencies with existing sub-regional IRWMPs such as those prepared in Butte and Shasta counties, and those currently developing plans, such as Yuba and Yolo counties. Given the broad range of interests across the valley, development of mutual objectives was an important step in building cooperation and identifying common interests and will be critical to the success of the IRWMP and its implementation. The following five objectives were identified as the foundation of this IRWMP to guide its implementation:

Adoption of IRWMP

- Over 40 water purveyors adopted the plan
- Ducks Unlimited, California Waterfowl Association, the Sacramento Valley Landowners and Family Water Alliance provided letters of support for the plan
- Every county across the Valley passed resolutions of support for the plan
- JEP adopted the plan

Objective 1 – Improve the economic health of the region

Improving the economic and environmental health of the region is intended to sustain the regional agricultural and urban economy while enhancing other economic opportunities throughout the region.

The IRWMP identified six of the eight counties in the plan area as economically disadvantaged communities, further emphasizing the challenges these counties are facing in meeting needed services as the population is increasing. Population growth in the region resulted in increased and changing water needs and associated infrastructure, flood protection, groundwater management, and other water-related issues. The implementation of the IRWMP provides these communities with the increased flexibility to meet their long-term water supply needs and protect water rights and the economies they support in the region.

Objective 2 – Improve regional water supply reliability for local water users, the region, and California

Meeting annual average and critical period demands and minimizing shortages by identifying regional and local supplies which contribute to regional water supply reliability. Some of the added benefits of improved local water supply reliability include:

- Protection of water rights and area of origin supplies
- Improved groundwater management

- Improved regional water management
- Contributing to statewide water supply reliability

Objective 3 – Improve flood protection and floodplain management.

This objective is focused on ensuring flood protection for the health and safety of the region's population while minimizing flood damage losses and seeking a balanced water management solution with respect to urban development in floodplains.

Objective 4 – Improve and enhance water quality.

As the region continues to grow, this objective focuses on improving the understanding of water quality cause/effect relationships at a local and regional level, and taking actions as warranted to improve water quality to support and enhance beneficial uses of water.

Objective 5 – Protect and enhance the ecosystem.

This objective promotes wise stewardship of land and water throughout the Sacramento Valley. It includes the protection and enhancement of habitat for fish, water fowl, and other terrestrial species and associated important riparian and wetlands habitat.

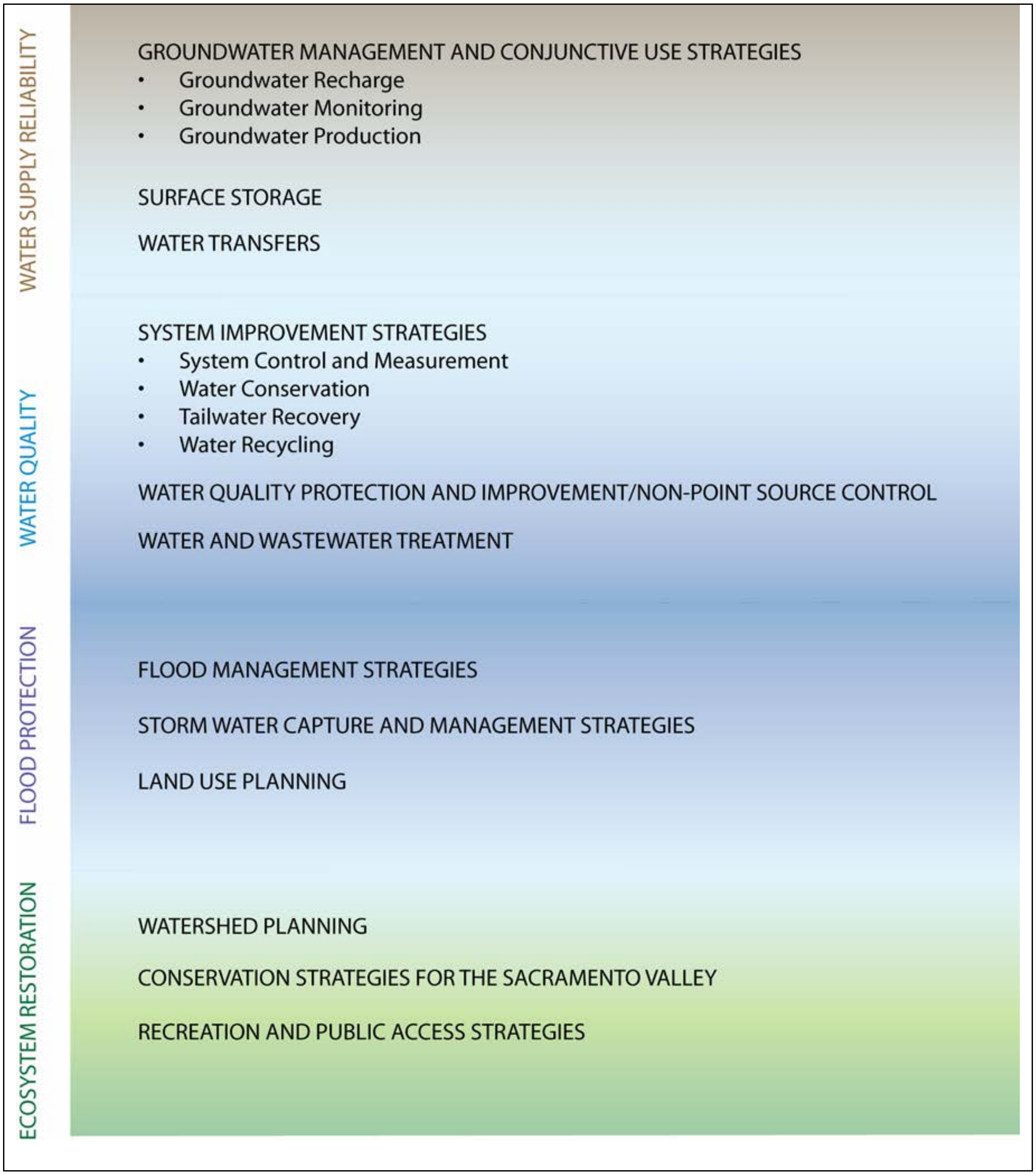
Regional priorities identified for the IRWMP include improving water supply reliability, protection of water rights, and flood protection. Priorities are given to the strategies and projects that provide multiple benefits and meet multiple objectives established for the region.

Water Management Strategies

A wide range of water management strategies were developed to meet the objectives identified in the planning process. The strategies are formulated to meet local water management needs and address water management issues of the region. The water management needs were identified through extensive discussions between water interests in the Valley. Specific projects and programs are also identified in response to the water management strategies. The result is a collection of projects that are considered technically, economically, and environmentally feasible while ensuring each project is consistent with and supports the IRWMP objectives and priorities agreed upon for the region.

During the planning process, 20 different water management strategies were evaluated in the context of four primary categories: water supply reliability, water quality, flood protection, and ecosystem protection. Applicable water management strategies were identified and analyzed in a manner that was agreed to best meet local needs.

An overarching essential consideration in linking the strategies is to provide assurances to all parties that implementation of the IRWMP was agreed to be the need to **promote economic health and viability** while ensuring no action will harm an entity or resource in the region. This approach ensured that projects will complement each other in attaining regional water management objectives.



Water Management Strategies and Objectives

Plan Implementation and Prioritization

NCWA, as the administrator of the JEP, will be responsible for providing continued coordination among the local agencies and with the state and federal agencies. NCWA will provide for a regional focus for the implementation of the IRWMP. The local agencies will be responsible for developing and implementing the projects. The implementation of certain parts of the IRWMP may be contingent upon securing funding from state and federal sources to supplement local cost share contributions. The IRWMP implementation will have significant statewide water quality and supply reliability benefits; therefore local agencies expect that the state should be actively engaged in funding the implementation of these projects.

The NCWA may coordinate and facilitate implementation of projects and programs, many of which simultaneously meet several local and or regional objectives and priorities. Implementation prioritization is based on the following criteria:

- Meeting the Sacramento Valley IRWMP objectives
- Providing for multiple benefits
- Readiness of projects and programs for implementation
- Availability of local funding and/or state/federal sources depending on scale of project

Implementation of the IRWMP is intended to result in numerous benefits including:

- Significant improvement in water supply reliability for local use, the region, and the state, including during drought conditions
- Additional water supplies to help meet water quality standards both within the region and in the Bay-Delta
- Improved water quality through the continued efforts of the Water Quality Coalition and implementation of system improvement strategies across the region
- Enhancement of water-dependent environmental assets including fisheries and terrestrial habitat in the valley and improved land management
- Improved understanding of the region's water resources, including understanding of potentially increased use of the Lower Tuscan Aquifer, and focused regional monitoring to ensure groundwater is used in a sustainable manner
- Improved flood management both locally and regionally
- Improved coordination across water districts, counties, and the region through sharing of data, ideas, and mutually beneficial management opportunities
- Coordinated implementation of water management strategies and associated projects

Multi level groundwater monitoring stations provide valuable data for understanding of region's groundwater resources.

<u>Recommendations for Successful Integrated Planning</u>

As Sacramento Valley water leaders continue their efforts to improve and enhance water management and quality throughout the region within the current regulatory framework, we present the following themes as initial, over-arching, recommendations to assist in the development of a successful integrated regional planning process. Many of these recommendations may seem self-evident, but can be easily overlooked and, in our experience, are key to moving forward in a successful manner.

Understand the culture in the region. The key to successful water programs is an understanding of the regional culture and the human dimension within this culture. This is particularly true for rural settings. The Sacramento Valley, as an area with rich water supplies, is a senior water rights culture with numerous provisions designed to protect the region's water supplies into the distant future. As such, the Sacramento Valley is driven by a sacred vision that both present and future water needs will be met in the region for farms, waterfowl, fish, cities and rural communities. Less populous than other portions of the state, those who live and work in valley value its rural nature, resources, and amenities. There have been many efforts during the past half-century to redirect water from this region, which has led to confrontation and in many cases litigation. Future efforts to redirect water will also receive vehement opposition.

On the other hand, the positive energy that has developed in the Sacramento Valley over the past decade, whether for fish passage, the SVWMA or the other programs described above, is built upon the fundamental recognition and protection of these water rights. As such, an understanding of this culture provides a strong foundation for regional and local planning. All regions have a distinct culture that must be understood and respected in order to move toward innovative solutions.

Preserve the important physical assets within a region. In addition to the human dimension, every region has unique and inter-dependent geographic attributes that should be recognized and preserved. In this case, the Sacramento Valley is a unique mosaic of farmlands, waterfowl habitat and spawning grounds for numerous fish species, as well as the water supply source for much of California. The valley's populace, whether landowners or local/state/federal agency representatives, want to preserve these important attributes and to maintain this unique working and natural landscape. The leaders in the Sacramento Valley have recognized that a regional approach is necessary to not only recognize the unique nature of this region, but also to collectively act in order to shape integrated planning and implementation in such a manner that reflects these attributes and will help preserve the physical assets in the region. Recognizing the assets of a region as well as perspectives related to use and protection of these assets is key to developing mutually beneficial options.

Facilitate the ways areas organize and ensure autonomy. The way in which local parties and entities join together with a common mission is very powerful and is key to successful integrated planning. In rural areas, for example, citizens tend to be very independent and averse to being a part of organizations. Additionally, there are many rural areas that are not located within an existing municipality or special district. It is therefore important to recognize that rural areas organize and govern very differently than urban areas and efforts to force urban governance on rural areas (and vice-versa) is not productive and is doomed for failure.

In the Sacramento Valley, partnerships are the foundation for the regional programs and the way people and entities organize. The IRWMP was formed organically in the Sacramento Valley and is now organized around various agreements articulating the unique partnerships and respective roles within the region. Interestingly, these partnerships have emerged at three important levels:

the local, sub-regional and regional levels, all of which are important and reflect the natural manner in which partnerships emerge for water planning. Central to these agreements is a deep respect for the autonomy held by the governing bodies of special districts, local governments and others within the region; while recognizing the importance and value of coordinating and in some cases jointly managing water resources. This type of organic organization should be encouraged whether the regional area is urban or rural in nature.

Move at a pace that makes sense for the region. Every area and region has a tempo that is well suited for the region and for which the involved parties are comfortable. In our experience, the water leaders in the region push this tempo, but, in doing so, must be sensitive to assuring the key parties are comfortable with the planning and policy dynamics and that the leadership is not too far ahead of the other decision-makers in the region. A respect for and understanding of this tempo is key to successful regional planning and coordination.

Work closely with federal and state agencies to explore innovative solutions. In the water arena, working with federal and state agencies is essential to make meaningful progress for regional planning and management. In the Sacramento Valley, the federal and state agencies not only have regulatory authority, they also operate major water projects that have an effect on nearly all water management decisions in the region. These and other agencies across the country can be positive partners in the move toward regional management if engaged properly. It is essential to work with these agencies as much as possible and to partner with them in important areas to help advance the regional planning effort.

Promote active water resources management. Central to integrated regional planning is active water resources management. In a growing state like California, where the demands for water are coming from urban areas, the environment, recreation and new demands for agriculture, the status quo will not help meet these growing demands for water. As a result, integrated regional planning will require active, as opposed to passive, water resources management that includes the management of surface and groundwater resources. Water management goes well beyond the delivery of water or the protection of the water resources; it is dependent upon the ability of local water resources managers to manage the total mix of water resources to meet local and regional needs.

Integrate land use planning with water supply planning. With the premium on water supplies in California and the West, water supply planning cannot be conducted in a vacuum. Most notably, changes in land use can have a significant effect on water supplies and it is critical that land use decisions are made to assure that there are appropriate water supplies available to meet the land uses during all year types, including dry years. The coordination between land use and water supply agencies has in the past been limited and needs to be strongly encouraged. This coordination is essential for integrated planning and should be a significant part of any regional plan.

A NEW E-PLATFORM LAUNCHED TO PROPAGATE KNOWLEDGE OF THREE ROLES OF PADDIES

Chia-Chen Kuo[1]
Ming-Hua Tsai[2]
Chuan-Lin Lai[3]
Yi-Haur Shiau[4]
Chang-Wei Yeh[5]
Cherng-Yeu Shen[6]

ABSTRACT

The purpose of this paper is to launch a new platform for advocating three roles of paddies including production, life and ecology through the cross-field integration of the agricultural hydrology, information technology and children's picture book, which is novel. We translate literatures of paddies to popular content. Scientific visualization is applied to develop digital value-added content for enhancing effect according to computer graphics technologies. For developing the Internet channel, we take web-based architecture coupled with Java3D and Flash visualization as the main solution for engaging attention of virtual communities. Through the web browser, we present paddy knowledge that is based on the above-mentioned popular content related to three roles of rice paddies. Furthermore, for the general public, the tiled display wall is employed to build up a fixed-site channel.

In this paper, the demonstration of promoting interest in paddy fields has been established. Through exploring this digital paddy, not only children could be encouraged to learn, but also the public could accumulate the knowledge related to paddy fields.

[1] Associate Research Scientist – Learning Technology Division, National Center for High-Performance Computing, National Applied Research Laboratories; No.7, R&D Rd. VI, Hsinchu Science Park, Hsinchu 30076, Taiwan, R.O.C.; cckuo@nchc.org.tw
[2] Director – Department of Irrigation and Engineering, Council of Agriculture, Executive Yuan, R.O.C.; 37 Nanhai Road, Taipei, Taiwan 10014, R.O.C.; mhtsai@mail.coa.gov.tw
[3] Assistant Research Scientist –Learning Technology Division, National Center for High-Performance Computing, National Applied Research Laboratories; No.7, R&D Rd. VI, Hsinchu Science Park, Hsinchu 30076, Taiwan, R.O.C.; chuanlin@nchc.org.tw
[4] Assistant Research Scientist – Grid Application Division, National Center for High-Performance Computing, National Applied Research Laboratories; No.7, R&D Rd. VI, Hsinchu Science Park, Hsinchu 30076, Taiwan, R.O.C.; ihow@nchc.org.tw
[5] Assistant Research Scientist – Computational Science Division, National Center for High-Performance Computing, National Applied Research Laboratories; No.7, R&D Rd. VI, Hsinchu Science Park, Hsinchu 30076, Taiwan, R.O.C.; c00cwy00@nchc.org.tw
[6] Research Scientist –Learning Technology Division, National Center for High-Performance Computing, National Applied Research Laboratories; No.7, R&D Rd. VI, Hsinchu Science Park, Hsinchu 30076, Taiwan, R.O.C.; c00cys00@nchc.org.tw

INTRODUCTION

The history of paddy agriculture has already been over 300 years in Taiwan. However, agriculture's GDP (Gross Domestic Product) has suffered a near 30 % decline since the 1950s due to social change. The growth of industrial economics causes a significant cut in paddy field area. Paddy fields not only produce rice, they also have a beneficial influence on life and ecology. There is, therefore, a need to propagate information regarding the multi-functions of rice paddies to the public for environmental sustainable development.

There are some examples of digital technology applied to education and promotion is concerned. The U.S. Department of Agriculture develops kids' website and designs a cattle cartoon character to introduce animal husbandry products. On the website of the Ministry of Agriculture and Forestry of South Korea, cartoon characters combined with interactive animation are used to convey the importance of cultivation and ecology conservation. As for the Ministry of Agriculture, Forestry and Fisheries of Japan, numerous comics on the Internet are designed to display its history of progress. In Taiwan, the National Museum of Marine Biology & Aquarium builds kids' website to deliver knowledge by multimedia content. Cartoons and comics have the potential to strengthen recognition of digital information across the Internet. From another perspective, as a strategy for knowledge delivery, choosing local humane materials as content topics is the key step towards achieving success.

According to the investigation results of Internet broadband usage in Taiwan, the number of the households with Internet access has risen from 55% in 1985 to 74 % in 2006. As a result, the topics of information communication become more crucial in an information society. Following the trend of network communities, how to build up a system using Internet for promoting paddy functions is critical.

Given the above, the objective of this paper is to launch a new platform for advocating three roles of paddies including production, life and ecology through the cross-field integration of the agricultural hydrology, information technology and children's picture book (Figure 1), which is novel. We translate literatures of paddies to popular content. Scientific visualization, which becomes a popular tool with advance in computing capabilities, is applied to develop digital value-added content for enhancing display effects. For developing the Internet channel, we take web-based architecture coupled with Java3D and Flash visualization as the main solution for engaging the attention of virtual communities. Through the web browser, we present paddy knowledge on the basis of popular content. Furthermore, for the general public, the tiled display wall (TDW) is employed to build up a fixed-site channel.

CREATION OF POPULAR CONTENT

In order to raise a degree of universal service, we make an effort to translate paddy-related literatures to popular content. Cartoon characters (Figure 2) are designed to add interest. The success of the creation relies on the cooperation between the agricultural hydrologists and writers of children's picture books in this paper. The development of the popular content of three roles of paddies is presented in the following sections.

Visualization of Rice Growing

Kuo et al. (2002, 2004) and Huang et al. (2001) employed the 2DSOIL (Timlin, 1996) to analyze the process of crop growth and the distribution of the subsurface field. The data of the rice height and the groundwater elevation versus time are obtained by the numerical calculation of the 2DSOIL. The resulting information is integrated into rice graphics during the growing period. Then the numerical data are transferred into the visual animation on the Internet (Figure 3).

Moderating Effects of Microclimate

In recent years, the demand on moderating regional microclimate has increased rapidly due to global warming. One promising option for local warming mitigation is to maintain and develop rice paddies (Wu, 2005). Based on the simplified biological system model, Wu (2005) simulated the paddy-field temperature and proposed that paddies functioned as air conditioners for achieving thermal comfort. In this paper, the video is recorded to introduce the concept of moderating effects of rice paddies in temperature. Also, we create animations with cartoon characters to advance the users' knowledge of how paddies have cooling effects in summer and show warming results in winter (Figure 4).

Ecological Functions during Fallow

Ecological functions of paddy fields have recently decayed since the industrial progress to the point that pollution problems have been attributed to arising from human activity. How to prevent the more serious damage to the paddy ecosystem is therefore necessary. Lai (2005) considered the issue of aquatic fauna transition depending on whether or not there was water storage in fallow paddy fields, and assessed the impact of interference from urbanization. In this paper, we make the video films for stating the value in maintaining ecological functions of paddies by using the above research results. Moreover, the interactive content including life cycles, habitats, morphological characteristics, systematic status, etc of biological species in paddy fields is established for users to explore further (Figure 5).

CONSTRUCTION OF NETWORK PLATFORM

The recent global expansion of Internet usage has encouraged the growing number of promotion on information exchange to implement knowledge effectiveness. For developing the Internet channel, we take web-based architecture coupled with Java3D, Flash visualization and video streaming as the main solution for engaging the attention of virtual communities through the interactive cross-platform infrastructure (Figure 6). OpenGL is also used due to the developing demand on 3D drawing ability (Woo, 1997; Wright, 2000).

A challenge of this paper is to solve the severe delay problem caused by the massive amount of data needed for the paddy-field visualization with multimedia effects. Computer graphics technologies including space partition, hierarchical tree structure, view frustum culling (Hoppe, 1997; Hoppe, 1998), billboard, and collision detection are therefore applied to speed up the rendering processes for the approach of real-time display on the Internet under condition of the maintenance of image resolution (Naylor, 1995).

Through the web browser of the network platform, we present paddy knowledge that is based on popular content (Figure 7). The details of this platform are briefly introduced as follows.

Web Portal

On the basis of the characteristics of the convenience, immediateness, and mobility of Internet access, a web portal of three roles of rice paddies is constructed (Figure 8). The framework of this portal is described in the following sections:

Temple Movie Theater: There are videos and animations involving “Visualization of Rice Growing”, “Moderating Effects of Microclimate” and “Ecological Functions during Fallow”. Users can choose on demand through the web portal.

Digital Paddy Field Museum: Information about the history, culture, environment, etc related to paddy fields is collected and divided into “Village Life Hall”, “Crop Production Hall” and Ecology Hall”.

Paddy Field Ecosystem: Interactive animations present the ecosystem relative to paddy fields. Users can further explore the characteristics of biological species through a web browser.

Life Cycle of Paddy Rice: Through animations, four steps of cultivation of paddy rice are demonstrated furrowing, seedlings, fertilizing and harvesting.

Rice Convenience Store: In order to help users understand what kinds of foods are produced from rice products, the interactive games are designed. The game rule is users will get scores if they make right choices that are rice productions.

Bird vs. Bug: For adding interest to this portal, the game entitled “Bird vs. Bug” is presented on the Internet. Users have to feed birds and battle with bugs within time limitations. All cartoon objects appear at random in this game. If users need more information about biological species, they can conveniently visit “Digital Paddy Museum”, “Paddy Field Ecosystem”, and etc. of this portal through a hyperlink.

The spread of knowledge about the three roles of paddy fields is carried out by means of integrated multimedia content. The strategy of a game-playing situation is adopted to meet the edutainment goal of this activity. For generating spatial effects, we embed all of games, animations and videos into a 3D scene based on the above-mentioned technologies in the field of computer graphics. Users can enter this virtual paddy field and interact with the objects of this 3D scene (Kuo, 2004). The left of Figure 9 shows a setting map and the right of one displays a view of a location chosen by users.

APPLICATION OF THE TILED DISPLAY WALL

The TDW is a versatile and large display system with high resolution. For the general public, the TDW, which was constructed by National High-performance Computing of Taiwan, is employed to build a fixed-site channel for information diffusion. The key specifics of the TDW are: 1) scalability, 2) standard components and 3) resolution. This TDW, containing 12+1 nodes and 24 projectors, is designed to drive the paddy-content display on a scalable high-resolution platform. Each projector has a resolution of 1024 by 768, so the whole TDW can reach high resolution of 4096 by 2304. The connection between the nodes and projectors is built by the RS232 interface (Figure 10). The TDW, which served as a virtual classroom, may enable an increase in knowledge effectiveness, because it supports high-performance and high-resolution displays and allows multi-users receive content simultaneously (Figure 11).

In this paper, we reconstruct the 3D virtual paddy (Figure 12), which owns all of the above-mentioned content, through the TDW platform.

CONCLUSION

In this paper, the demonstration of promoting interests in three roles of paddy fields has been established by the collaboration among the agricultural hydrologists, information professionals and writers of children's picture book. In the first stage, we target on transferring paddy-related literatures into popular content with cartoon characters. The web-based platform is then launched to spread information including videos, animations, games, etc. Finally, the 3D virtual paddy, which has a high resolution, is rebuilt as a fixed-site channel for knowledge diffusion on the TDW platform. Through exploring the digital paddy, not only children could be encouraged to learn, but also the public could accumulate knowledge related to paddy fields.

A follow-up is to empower this platform for paddy education. To engage attention of international communities is also our next milestone.

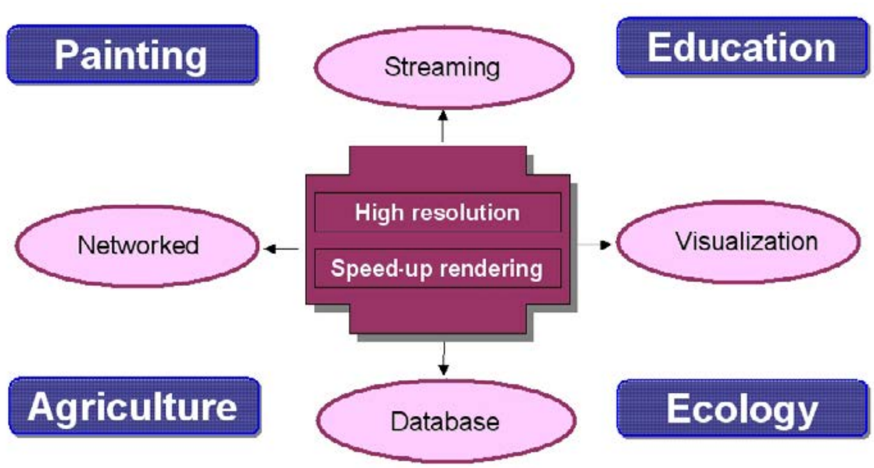


Figure 1. Cross-Field Integration for e-Platform Development

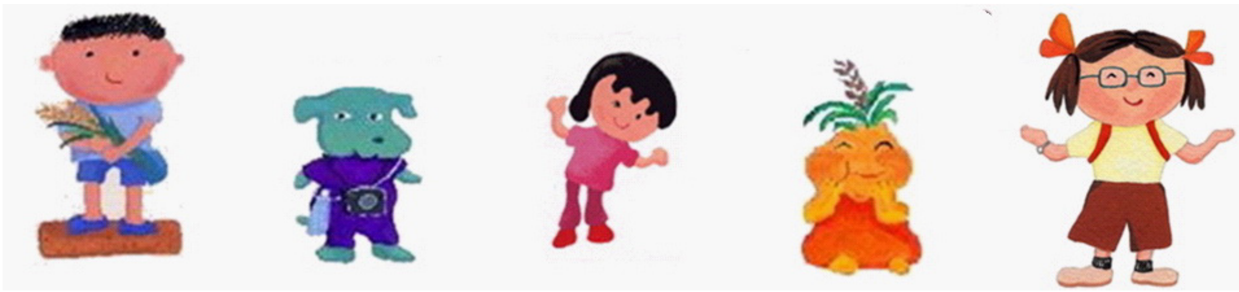


Figure 2. Cartoon Characters of Three Roles of Paddies

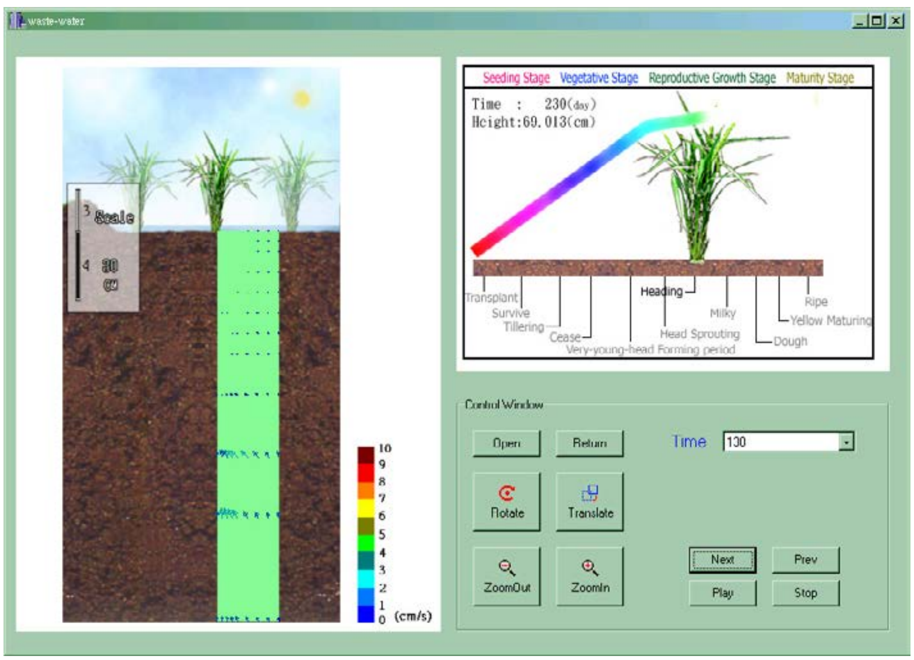


Figure 3. Animation of Rice Growing Analyzed by Numerical Computation

Figure 4. Popular Content of Moderating Effects of Microclimate in Paddies

Figure 5. Popular Content of Paddy Field Ecosystem

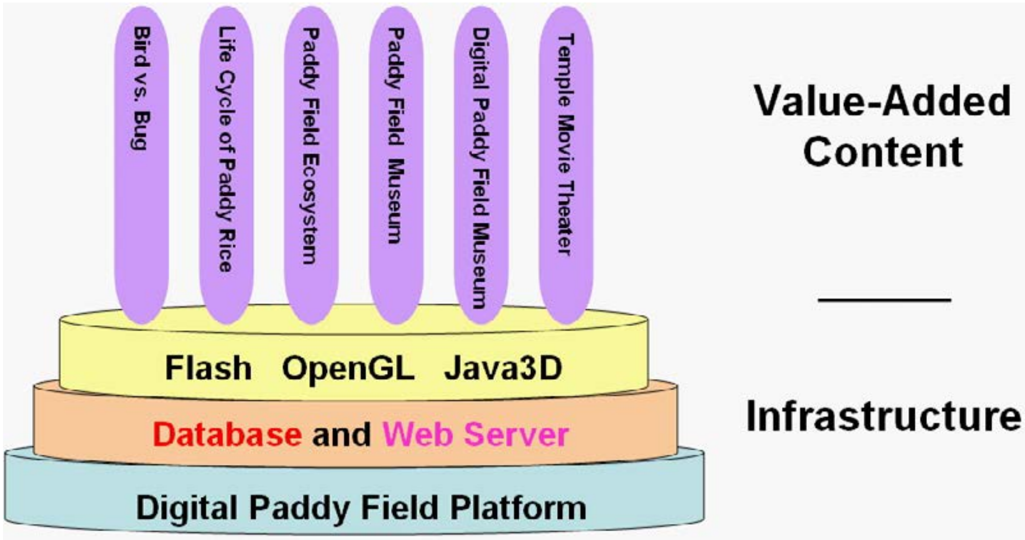


Figure 6. System Architecture of Digital Paddies

Figure 7. Homepage of Portal of Three Roles of Paddies

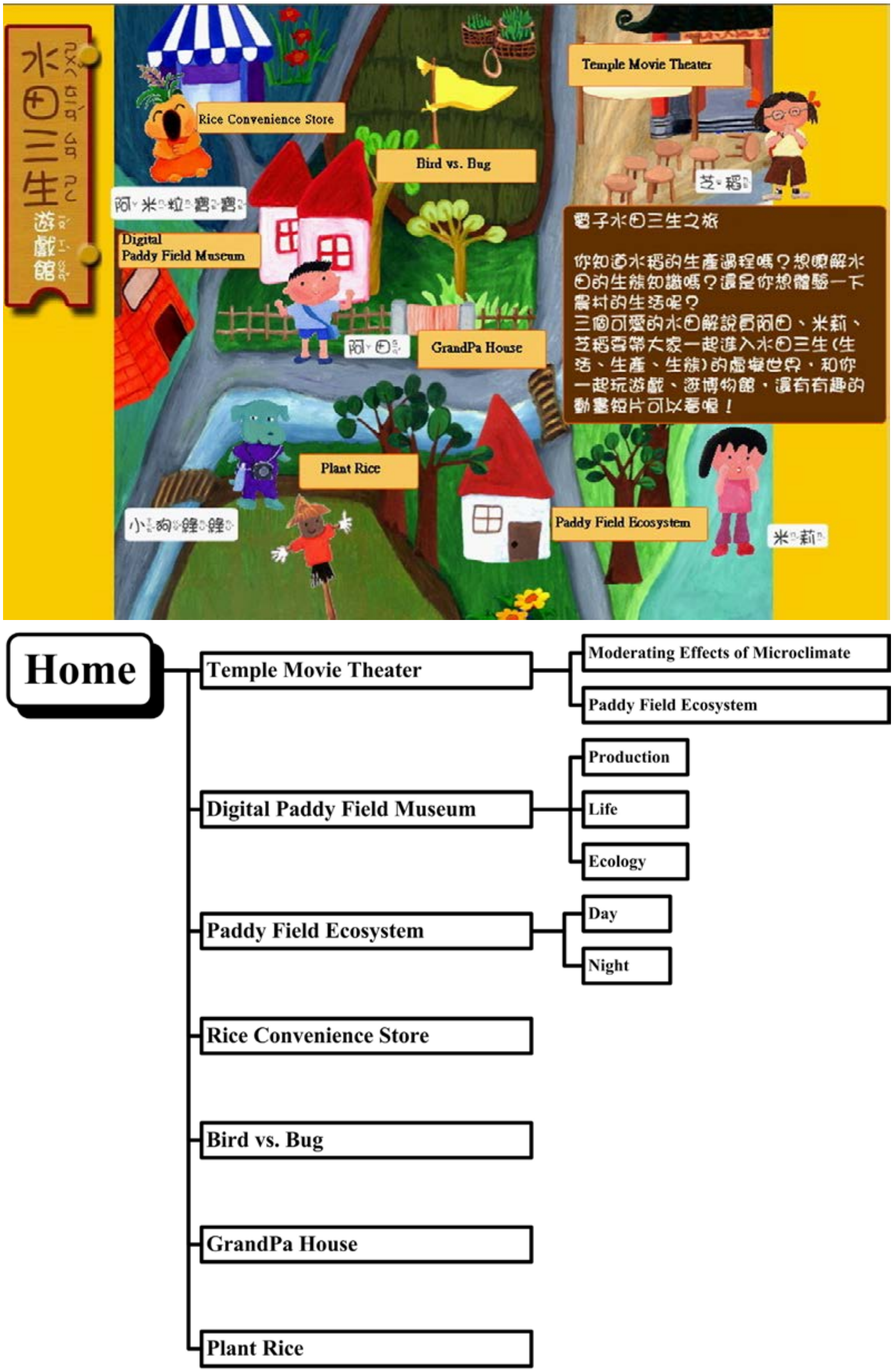


Figure 8. Content Structure of Portal of Three Roles of Paddies

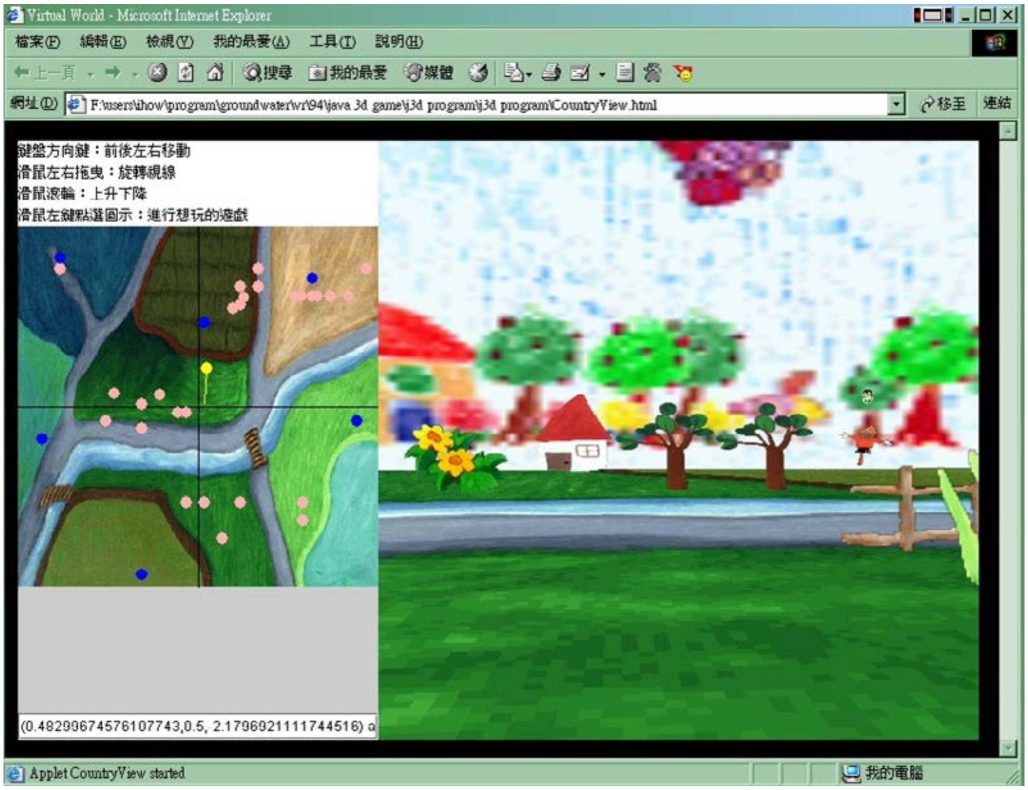


Figure 9. Illustration of 3D Scene of Virtual Paddies

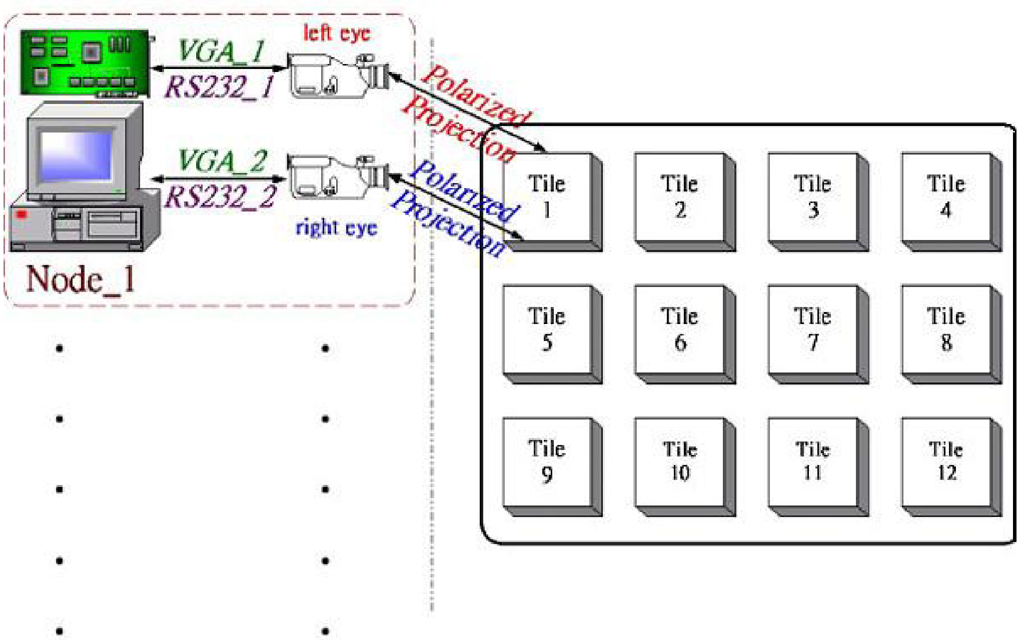


Figure 10. Architecture of the TDW

Figure 11. Illustration of Virtual Classroom of the TDW

Figure 12. Illustration of 3D Scene of Virtual Paddies in the TDW

REFERENCES

Huang, C. P., Kuo, C. C., Tsai, W. F., Cheng, H. P., Li, M. H., and Hung, M. T. (2001). Numerical Computation of Crops Growing affected by Nitrogen in Land. The 4th International Conference on High-Performance Computing and Grid in Asia Pacific Region '01, Australia.

Hoppe, H. (1997). View-dependent refinement of progressive meshes. In Proc. SIGGRAPH '97, pp. 189-198.

Hoppe, H. (1998). Smooth view-dependent level-of-detail control and its application to terrain rendering. In Proc. IEEE Visualization ’98, pp. 35-42.

Kuo, C. C., Huang, C. P., Shiau, Y. H., Tsai, W. F., and Yang, K. S. (2002). Scientific Visualization Applied to Analyze Crop Growing in Land. Hydroinformatics’02, Cardiff, U.K.
Kuo, C. C., Huang, C. P., Shiau, Y. H., Shen, C. Y., and Tsai, W. F. (2004). The Web-based modeling system for the 2DSOIL model. Hydroinformatics ’04, Singapore.

Kuo, C. C., Shiau, Y. H., Huang, C. P., Shen, C. Y., and Tsai, W. F. (2004). Application of Virtual Reality in Ecological Farmland Navigating System. The 7th International Conference on High-Performance Computing and Grid in Asia Pacific Region ’04, Japan.

Lai, H. T., and Shy, J. Y. (2005). Investigation and Restoration of Aquatic Communities in Fallow Paddy Fields. Sustainable Management and Environment Functions of Paddy Conference, pp. 195-209.

Naylor, B. F. (1995). Interactive Playing with Large Synthetic Environments. Interactive 3D Graphics, p107-108.

Timlin, D., Acock, B., and Genuchten, R. (1996). 2DSOIL - A Modular Simulator of Soil and Root Processes. Release 03, Remote Sensing and Modelling Lab, Beltsville, MD and Soil Salinity La.

Woo, M., Nedier, J., and Davis, T. (1997). OpenGL Programming Guide: the Official Guide to Learning OpenGL. Version 1.1, Addision Wesley, pp19-223.

Wright, R., and Sweet, M. (2000). OpenGL SuperBible. Version 2.0, Waite Group Press, 200, Tamal Plaza, Corte Madera , CA 94925.

Wu, F. C., and Fang, C.I. (2005). Microclimate and CO2 Flux Models for Paddy Field Eco-environment. Sustainable Management and Environment Functions of Paddy Conference, pp. 1-18.

EFFECT OF NETWORK WATER DISTRIBUTION SCHEDULE AND DIFFERENT ON-FARM WATER MANAGEMENT PRACTICES ON SUGARBEET WATER USE EFFICIENCY — CASE STUDY: MAHABAD, I.R. IRAN

Shahab Daneshvar[1]
Ali Reza Shokoohi[2]
Karim Shiati[3]
Farshid Morshedi[4]

ABSTRACT

Application of different irrigation management practices plays a considerable role in water saving to achieve potential yields. On the other hand, network water distribution schedule is a governing factor in this regard. In current study conducted in Mahabad plain in North West of Iran, four different irrigation managements on sugarbeet cultivation including traditional farmer's management, Furrow Deepening, Reduced Discharge per Deepened Furrow, and Alternate Furrow Irrigation have been studied in real farmers' fields measuring 10.2 hectares. Participatory management approach has been used while working in farmers fields. Soils textures are silty clayey. Results of studies indicate that water used has been reduced considerably while higher root and sugar yields are obtained due to better on-farm water management practices. Water Use Efficiency, in kg of yield per m^3 of water used, increased considerably under alternate furrow irrigation management in comparison to what obtained under traditional management. Results show application of alternate furrow irrigation in sugarbeet cultivation not only resulted in lesser water use per hectare, but also it increased both root and sugar yields and, consequently, higher water use efficiency was obtained. Assessments have been made on irrigation schedule imposed by the irrigation network and its effects on actual water requirements. Results show that the delivery schedule practiced in the network in incapable of delivering the actual amount of water requirement for the dominant crop of the scheme. Suggestions are made to the network operator to improve overall network efficiency including revisions on water resources planning and allocation and/or improve network operation system.

INTRODUCTION

The increasing population in the Lake Uromiyeh region places increasing demands on water for drinking, industry and for food production. Out of this total demand, irrigation consumes 95% of all the available water. The water resources are limited. More and more rivers are controlled by dams and reservoirs in order to increase the availability of water. Where no surface water is

[1] Project Manager – Mahab Ghodss Consulting Engineering Company, P.O. Box: 19395-6875, Takharestan st., Dastgerdi st., Tehran, Iran, Zip Code: 1918781185, Email: Daneshvar@MahabGhodss.com
[2] Assistant Professor – Imam Khomeini International University, Ghazvin, Iran, Email: Shokoohi_ar@ikiu.ac.ir
[3] Head of Water Resources Department, Yekom Consulting Engineers, Tehran, Iran, Email: Karim.Shiati@Yekom.com
[4] Project Manager – Mahab Ghodss Consulting Engineering Company, P.O. Box: 19395-6875, Takharestan st., Dastgerdi st., Tehran, Iran, Zip Code: 1918781185, Email: Morshedi@MahabGhodss.com

available, wells are constructed to conduct the irrigation. In spite of the scarcity of water, the irrigation methods applied in many regions in the Uromiyeh basin are highly inefficient. It is estimated that the average efficiency of irrigation systems is about 35%. The inefficient irrigation methods cause severe damage to the irrigated areas. Also the groundwater tables in many basins are decreasing rapidly as a result of over-pumping, leading to salt water intrusion from the lake and the death of hundreds of hectares of orchards.

Conventional irrigated agriculture enjoyed an abundant availability of water. Since water was not a scarce resource, this led to irrigation methodologies with low water use efficiencies and resulted in overuse of water, seepage, and development of waterlogging and salinity in the downstream areas. The intensification of use of the limited water resources and the intended expansion of irrigated area will lead to a strain on the availability of water on farm level and require improvement of the waterlogging and salinization of the downstream areas, which are now intended to be used for agriculture as well. The increased environmental awareness in Iran does not tolerate a deterioration of the land through waterlogging and salinization either. In order to make it technically possible and socially acceptable to irrigate with less water while obtaining similar or higher yields new methodologies should be developed and demonstrated.

Kang et al. (1998) studied three treatments on furrow irrigation management including fixed, alternate and conventional irrigation in maize cultivation. Results indicated that number of preliminary root, total dry root, and root intensity are higher under alternate furrow irrigation in comparison to the other two irrigation managements. Also, higher water use efficiency was obtained in this method. Kang et al. (2000) reported that incorporating alternate furrow irrigation in maize cultivation has resulted in 35% reduction in water use, while only 6-11% reduction in dry material occurred. Fischback and Mulliner (1972) reported alternate furrow irrigation for maize cultivation has resulted in 29% reduction in water use while only 4.7% reduction in dry material occurred. Studies of Stone et al. (1979) indicated that amount of evapotranspiration in alternate furrow irrigation is less than that of achieved under conventional management. Raine (1999) reports that studies of Bakker et al. (1997) on alternate furrow irrigation have shown that significant water use reduction would be achieved while insignificant reduction in yield occurred. Raine (1999) also reports the studies of Torres et al. (1996) on alternate furrow irrigation in sugarcane cultivation that has shown 40% water use reduction against 38 ton/ha reduction in yield. Box et al. (1963) and Raine (1999) report results of several studies regarding incorporation of alternate furrow irrigation in potato, onion, wheat, maize, sorghum, and cotton cultivations with 50% reduction in water use. Also, due to potential increase in water use efficiency by using this method, it is a highly preferable method to be incorporated in areas with scarce water resources.

METHODS AND MATERIALS

Approach

The practical validity of the methodology of reduced water use has to be proven to, and accepted by the farmers, the ultimate users. To assure that the results are applicable by the farmers, it was decided to conduct the studies in a participatory way by fully integrating the farmers in the selection of the areas, the development and testing of the methodology and the evaluation of the results.

The concept of the Pilot Water Management Studies (PWMS) is schematically shown in Figure 1. The final objective, reduced on-farm water use, is shown in the top of Figure 1. After a first cycle the same process could be followed again for further improvement and higher technology levels incorporation as indicated by the dotted arrow.

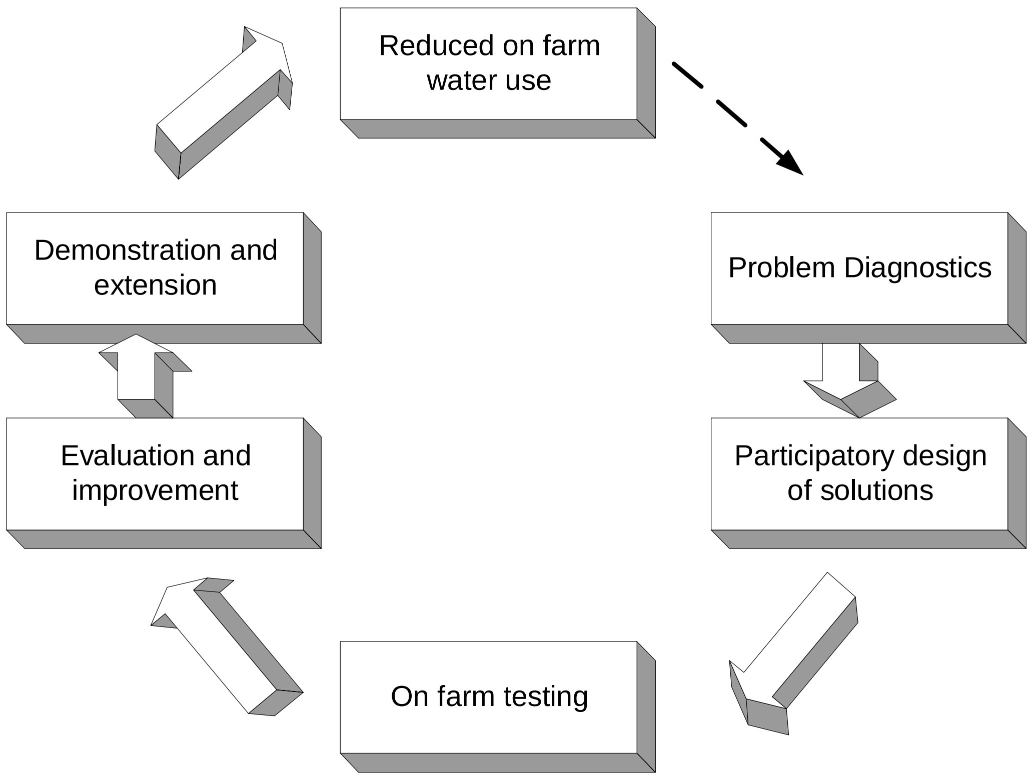


Figure 1. Conceptual Framework of the PWMS

The right-hand side shows the methodology to reach this objective, starting with the problem diagnoses in which main constraints to reach efficient irrigation are identified. The problem diagnostics are used as basis for the participatory design of solutions. The solutions are subsequently implemented for on farm testing, which is followed by an evaluation of the tests. The evaluation are used to improve the design and, if the evaluation is positive, the solutions can be disseminated through demonstration and extension, which will eventually lead to improved irrigation and reduced on-farm water use.

The irrigation techniques practiced in study area were investigated and assessed in general and around the PA more specifically. Interviews were conducted with farmers of the PA and in the Reference Area (RA). The monitoring focused on cropping patterns, yields, irrigation techniques and constraints with respect to irrigation and agricultural production. In several workshops and field sessions, a participatory problem inventory of present irrigation practices and the related problems was carried out, with farmers, and City Jihad Agricultural Management (CJAM) and Agricultural Service Center (ASC) staff. The diagnostic outcomes formed the basis for the design of the treatments. During the study period, a qualitative understanding of the causes and effects of over-application of irrigation water at farm level for the dominant crop (sugarbeet) has been developed. This understanding is summarized in the problem tree shown in Figure 2.

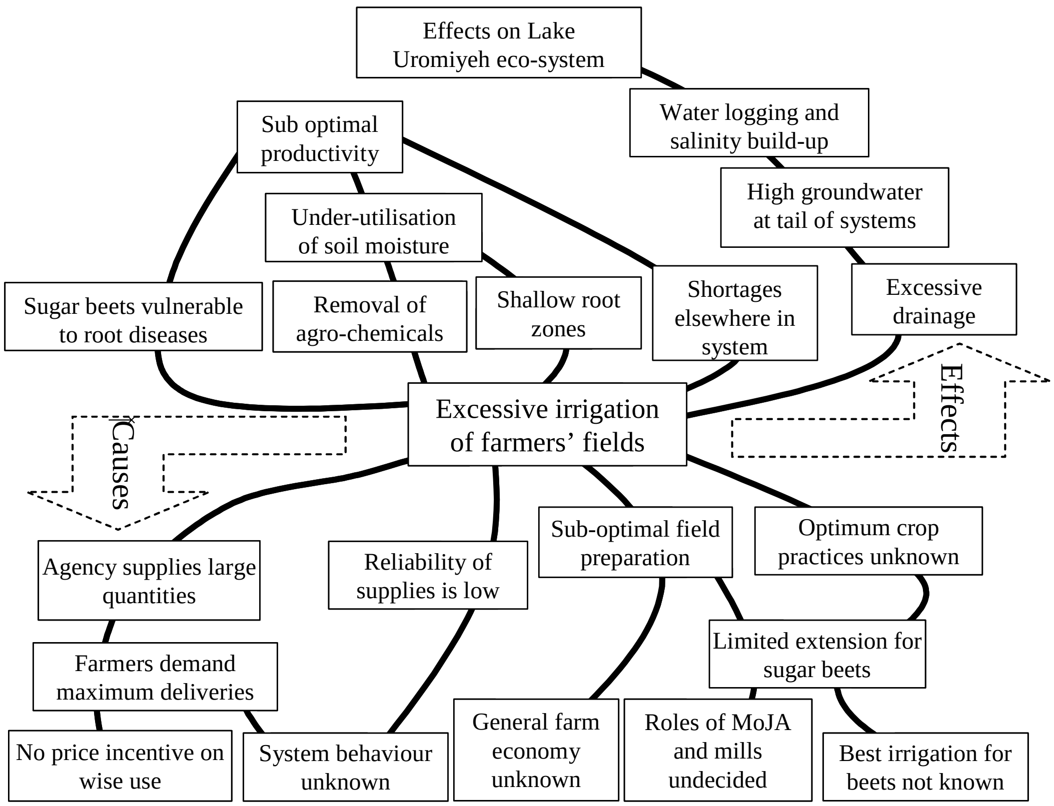


Figure 2. Problem Tree Analysis of Excessive Irrigation of Sugarbeet in Study Area

<u>Pilot and Reference Areas</u>

Mahabad Pilot Area is located in the eastern part of the Mokriyan Irrigation System. The management of the main infrastructure is undertaken by the Water Authority, through an Operation and Maintenance Company (OMC). An alternative pilot site in West Mokriyan was discarded as its less reliable water supply and its smaller plot size could compromise the quality of the tests. The pilot area consists of three farms, and it measures about 7.0 ha. The external reference area selected in this region consists of one farm measuring 2.1 ha. Soils in these farms are silty clayey, fields are between 1.4 and 4.7 ha in size and 85-280 m long. The fields are uneven and they have an irregular micro-topography that jeopardizes proper on-farm irrigation water control and distribution. Sketches of all farms included in pilot and reference areas are shown in Figures 3 to 6.

Treatments

The treatments focused on testing:

1) Better irrigation water distribution on field and increasing infiltrating water into the field (DF);
2) Reduction of tail-end runoff and increasing infiltrating water into the field and better irrigation water distribution on field, tried out were:
   - Deepening Furrow with Less Discharge per Furrow (DFLD);
   - Alternate Furrow Irrigation (AFI).
3) Reference Areas: Neither change nor improvements were made in this treatment. When located in pilot farms, these are considered as *Internal Reference* (IRFM) and when they are located in reference farms, they are considered as *External Reference* (Ref.).

All treatments have been tried out with three replications each except the external reference area, which consists of one complete farm. Treatment number 1 (IRFM) is an internal reference itself. Results of this treatment and results of the external reference area are averaged and considered as Reference (Control) for assessment of conducted treatments, i.e. treatments 2 to 4 (DF, DFLD, and AFI). Results of these two reference areas are shown separately and statistically compared with other treatments to have an idea of differences between internal and external references, but as mentioned above, averaged results of the two references are used in final comparisons. In all treatments crop was Sugar beet, and irrigation method was Furrow irrigation. Also in all treatment it was decided that one irrigation turn is omitted at the end of growing season. In this respect, during the last 80 days before harvest, there were 3 irrigations applied in all reference plots, whereas only 2 irrigations were applied in all treatment plots. This practice has a twofold purpose: 1) totally less water is used, and 2) sugar content is increased without significant reduction of the root yield.

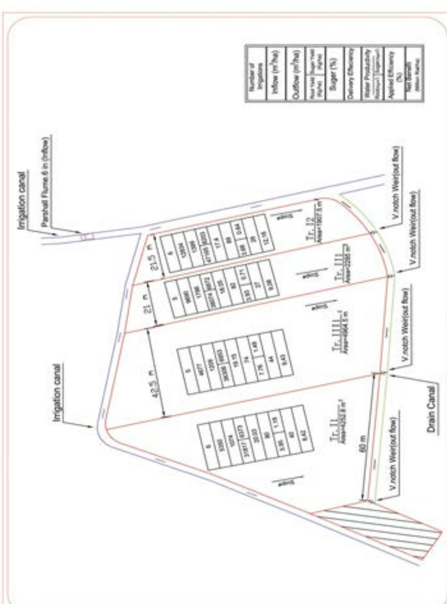


Figure 3. Pilot farm no. 2-1 (1.4 ha)

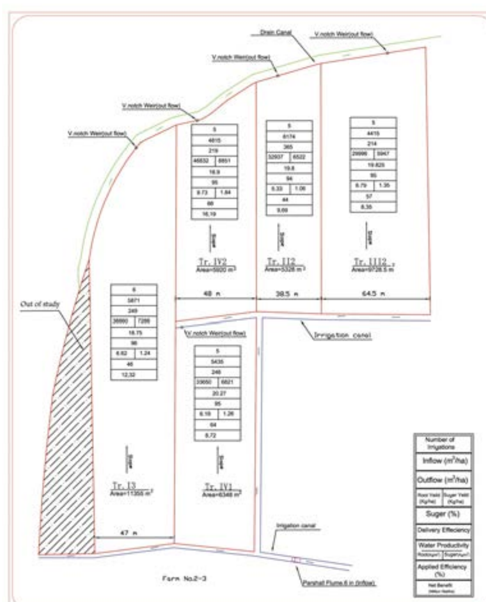


Figure 4. Pilot farm no. 2-3 (4.7 ha)

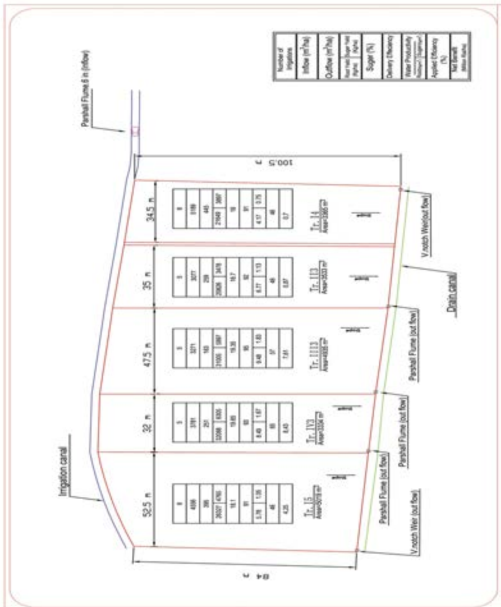


Figure 5. Pilot farm no. 2-4 (2.0 ha)

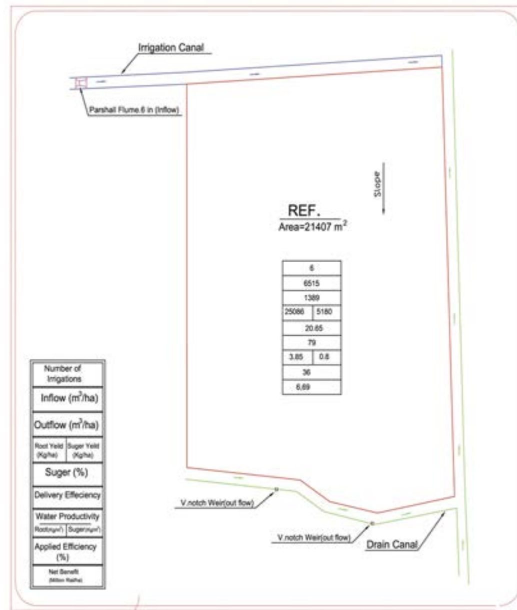


Figure 6. Ext. Ref. farm no. 2-2 (2.1 ha)

RESULTS

The indicators values for the treatments in the pilot area and the reference areas are given in Table 1. The treatment shown in bold represents the best treatment tried out, i.e. alternate furrow irrigation.

Table 1. Summary of Water Use, Yields, Efficiencies and Net Benefits

Treatment	Water use	Yield		Efficiencies					Net Benefit
		Root	Sugar	Water Use		Delivery	Application	Monetary Water Use	
				Root	Sugar				
units	m^3/ha	kg/ha		kg/m^3		%	%	IRR/m^3	10^6IRR/ha
DF	6314	30612	5624	5.34	0.97	89	39	1050	6.63
DFLD	4121	32436	6299	8.01	1.56	88	53	2072	8.54
AFI	**4677**	**37523**	**7326**	**8.14**	**1.59**	**94**	**65**	**2393**	**11.19**
Reference	6638	29125	5643	4.55	0.89	84	39	1103	7.33

During the spring season 2004 water use in the entire Pilot Area in Mahabad area was reduced with 24% compared to the reference area while yields, root and sugar, were slightly higher, both similarly about 15%, than in the reference area.

The Alternate Furrow Irrigation (AFI) treatment obtained highest yields (37523 kg/ha root yield and 7326 kg/ha sugar yield) with second lowest total water applications (4677 m^3/ha). All other treatments also resulted in higher yields than the reference, while total water application didn't exceed that of the reference, too. Also, treatment DFDL produced more sugar per ha than the reference, while treatment DF production was lesser.

Average water use and *yields* for the different treatments and the reference are shown in Figures 7 and 8 for root and sugar yield, respectively. *Water Use Efficiency*, in kg of yield per m^3 of total water used, is shown in Figures 9 and 10 for root and sugar production, respectively. *Net benefit*, in 10^6 Islamic Republic Iran Rials (IRR) per ha, is shown in Figure 11, left bars and left Y axis. *Monetary water use*, in Net Benefit in IRR per m^3 of total water used, is shown in Figure 11, right bars and right Y axis. *Application Efficiency*, in %, is shown in Figure 12. In application efficiency calculations an engineering judgment based irrigation water distribution factor is considered for different treatments and reference areas. The considered distribution uniformity factors are 0.5, 0.5, 0.6 and 0.7 for reference areas, DF, DFLD, and AFI treatments, respectively.

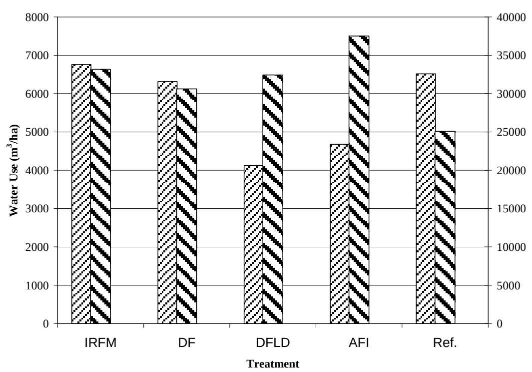


Figure 7. Average water use and root yields

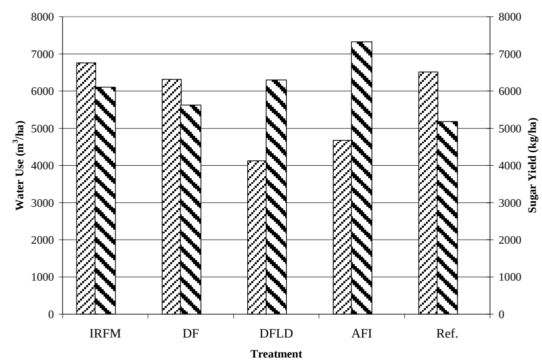


Figure 8. Average water use and sugar yields

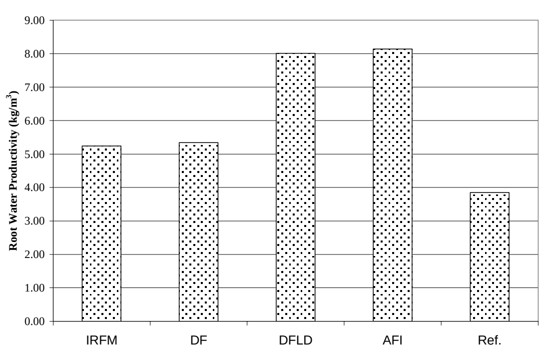


Figure 9. Water use efficiency in root production

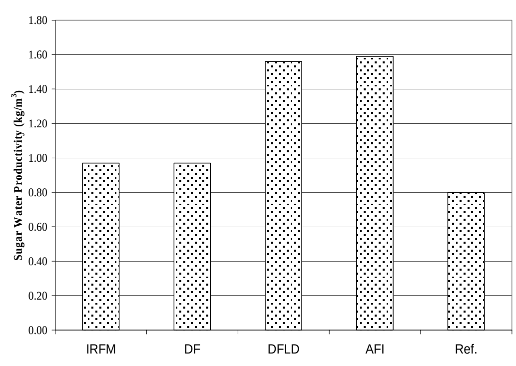


Figure 10. Water use efficiency in sugar production

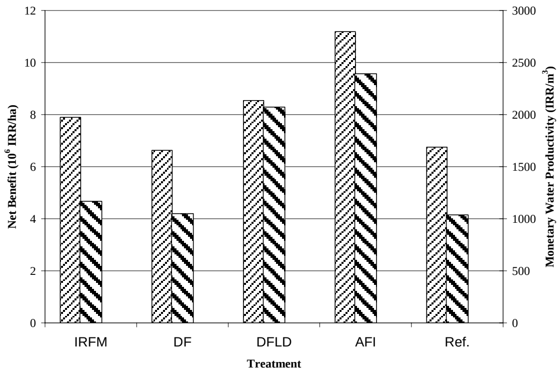


Figure 11. Net Benefit per ha and Monetary water use efficiency

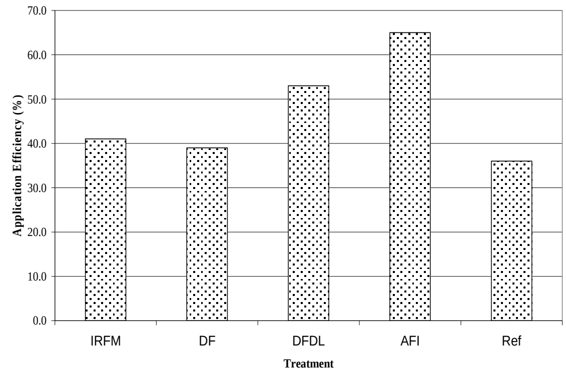


Figure 12. Average application efficiencies

DISCUSSION

Treatments are statistically analyzed and compared using One Factor Randomized Complete Block Design method. It should be noted that, as mentioned previously, with deepening of furrows it was aimed to have a better irrigation water distribution on field and also increase amount of infiltrating water into the field. However, in practice it was found that this solution would not make any considerable change in management. This happened due to uneven micro-relief of farms. Therefore, after the first two irrigations, deepening of furrows discontinued. As a result, treatment DF is actually the same as reference area and treatment DFLD is actually LD, i.e. less discharge per furrow.

Difference of ***water use*** between AFI and DFLD treatments and DF treatment is statistically significant (α=10%). However, difference between average water use in these two treatments and the reference area is not significant. Difference of ***tail-end outflow*** between treatment AFI and external reference area is statistically significant (α=5%). Difference of ***root yield*** between treatment AFI and reference area (both internal and external reference areas) is statistically significant (α=10%). Amounts of root yield produced under other treatments are not statistically different. Moreover, difference of this factor between AFI and DFLD treatments and external reference is significant (α=5%). Difference of ***sugar yield*** between treatment AFI and reference area (both internal and external reference areas) is statistically significant (α=5%). Moreover, difference of this factor between AFI treatment and external reference is significant (α=1%).

Difference of ***root water productivity*** between AFI and DFLD treatments and both internal and external references is statistically significant (α=5%). Moreover, difference of this factor between AFI treatment and external reference is significant (α=1%). Difference of ***sugar water productivity*** between AFI treatment and both internal and external references is statistically significant (α=1%). Difference of ***net benefit*** between AFI treatment and both internal and external references is statistically significant (α=5%). Difference of ***monetary water productivity*** between treatment AFI and both internal and external references is statistically significant (α=5%). The ***delivery efficiency*** (ratio of infiltrated water in the field to the delivered water to the field) for all treatments is in good range. However, it should be noted that since total inflow has been reduced, therefore, final tail-end outflow has changed considerably; i.e. about only 23% tail-end outflow is produced in AFI treatment comparing to reference area.

The main physical bottlenecks common in Mahabad area could be summarized as follows:

Sub-optimal field preparation

The fields in this area have an uneven micro-relief. Fields are not well-levelled. The passage of water from the irrigation ditch to the furrows and again from the furrows to the tail-end drainage crosses perpendicular on the first rows of sugar beet. As a consequence, the areas up- and downstream of the furrows are watered in a very uneven way. Also due to sub-optimal field preparation, the depth of irrigation is uneven over the fields.

Shallow root zone

The impression exists that the transformation of the alluvial deposits in Mahabad to a deep soil profile, progresses very slowly. A modest moisture stress promotes deep penetration of roots, which in the end helps deepen the soil profile and thereby the storage of water in the root zone.

Irrigation Frequency

As mentioned in application efficiency discussion, according to Mahabad scheme operation program fields would receive only 6 irrigation gifts during spring growing season. This little number of irrigation turns together with shallow root zone in the area result in an uncontrolled deficit irrigation in the area.

High Groundwater Table

It should be noted that there is no potential hazard of soil salinization in Mahabad attributed to irrigation water. However, high groundwater table is a critical problem in most areas in Mahabad plain, especially at tail of irrigation system that would result secondary soil salinization through capillary rise. This phenomenon was not addressed in studies. But it is recommended to conduct specific study to address this issue. The high groundwater table also prevents root development and penetration, which results in poor crop stands and under-utilization of soil moisture.

CONCLUSION

Results show that application of alternate furrow irrigation in sugarbeet cultivation not only resulted in lesser water use per hectare, but also it increased both root and sugar yields and, consequently, higher water use efficiency was obtained.

In Mahabad yields improved and water use was reduced significantly by improved control over the irrigation. Better uniformity of on-field water distribution through irrigating alternate furrows in each irrigation turn and reducing inflow into each single furrow were key factors in improving irrigation efficiencies and crop yields.

Treatments AFI and DFLD resulted in water productivity close to the maximum expectable values reported. The range of water productivity for sugarbeet reported by FAO is between 6 and 9 kg of product per m^3 of water used. In this regard, treatments AFI and DFLD resulted in water productivity more than 8 kg per m^3 of water used. It should be noted that water productivity in reference area is considerably lower than the minimum value reported by FAO, i.e. 4.55 kg/m^3 against reported value of 6 kg/m^3. It shows that current sugarbeet production in Mahabad plain is very inefficient.

Total area under cultivation of sugarbeet in Mahabad area during spring season 2004 using surface irrigation was 1530 ha. About 20 percent of soils in Mahabad area have heavy texture. It was effectively shown that adopting alternate furrow irrigation would save up to 1950 m^3 per hectare in fields with heavy soils. As a result, application efficiency increased from 65%, which is 26% increase. It should be noted that officially reported application efficiency in Mahabad area is about 45%, which in this case application efficiency is increased by 71% resulting in roughly 1700 m^3 water saving per hectare. The studies were conducted on heavy soils and for sugar beet, however, it is possible to find practical solution also for other soil textures and crops to save water and increase application efficiency. Considering a sound value of 1500 m^3/ha of water saving as an average for the whole Mahabad area, consisting of 14088 hectares of irrigated lands that utilize surface water resources, it would be concluded that roughly 21.1 MCM water would be saved if better on-farm irrigation water management is practiced in the area.

Best sowing dates for sugar beet cultivation in Mahabad plain in Mahabad sub-basin is recommended to be in late March and early April, and preferably in the third decade of March. In Table 2 recommended dates of irrigations and relevant amount of irrigation gift is given. The figures are for one hectare of land with heavy soils.This table is develope to be considered by OMC of Mahabad irrigation scheme for future oprational planning of the system.

Table 2. Irrigation Interval and Application Quantity for Sugar beet in Mahabad Area

Interval	**Quantity**
days number	m^3/ha
Day 80	900
Day 95	900
Day 115	960
Day 135	960
Day 160	930
Total	5 irrigations (4650 m^3/ha)

The number of days given in above table represents number of days after sowing. The figures are flexible in a range of ± 5 days.

REFERENCES

Box J., Sletten W., Kyle J., Pope A. (1963), "Effects of Soil Moisture, Temperature and Fertility on Yield and Quality of Irrigated Potatoes in Southern Plains", Agronomy Journal, 55: 492-494

FAO, (1979), "Yield Response to Water", Technical Paper No. 33

Fischback P., Mulliner H. (1972), "Every Other Furrow Irrigation of Corn", ASCE paper, No. 72

Kang S., Laing Z., Zhang J., (1998), "Water Use Efficiency of Controlled Root-Division Alternate Irrigation on Maize Plants", Agricultural Water Management, 38: 69-76

Kang S, Laing Z., Yinhau P., Peize S., Jianhua Z. (2000), "Alternate Furrow Irrigation for Maize Production in an Arid Area", Agricultural Water Management, 45: 267-277

Raine S., (1999), "Research, Development and Extension in Irrigation and Water Use Efficiency", NCEI production No. 17297/4

Stone J., Garton E., Webb B, Reeves H., Keflemariam J., (1979), "Irrigation Water Conservation Using Wide Spaced Furrows", Soil Science Society of American Journal, 43: 407-411

Yekom Consulting Engineers, (2005), "Integrated Water Resources Management for Lake Uromiyeh Basin, Iran (PvW-02.048): Module 2- Water for Food: Assessment of Existing Irrigation Condition and Farm Water Management in Naghadeh and Mahabad Plain for Improving the Irrigation Efficiency – Part 2: Water Management on Farm to Increase Water Efficiency", 71 pages

STRATIFICATION OF POLITICAL WILL IN THE IRRIGATION TRANSFER PROCESS

L. Humberto Yap-Salinas[1]

ABSTRACT

When a project designed to implement irrigation system management transfer and/or other related plans for institutional transformation or when technological modernization is being considered in a developing country, one important factor in the short-term success and long-term sustainability of that project's goals must be considered: the currents and countercurrents of the bureaucratic environment of the water sector in that country and/or region. Differing and sometimes competing opinions and motives exist at different levels in the water sector bureaucracy. Thus, even while certain members of the upper levels of government (e.g., in the water ministry) may favor such a project, others at the same level, as well as mid-level and lower level managers may be opposed. This stratification of political will—a layering of behaviors toward the project—can strongly affect the speed of advance and final outputs of the project. Similarly, plans for long-term sustainability must take into account shifts in the layers of political will.

This paper explores these layers of political will—their causes, their relative weight, and their effects on water-managing institutions and on organization of the water sector. Also discussed are approaches to over come resistance. Lessons learned in thirty years of experience in implementing irrigation projects in several developing countries are shared.

INTRODUCTION

Political will is a term that, in the implementation of irrigation projects in developing countries, especially projects involving transfer of irrigation system management from government agencies or ministries to water users, refers to attitude and actions in favor of the success of implementation of a project. This will, or lack thereof (as shown by opposition), greatly affects a project's success and subsequent sustainability of results. There are layers and degrees of political will—stratification of political will—in all levels of government and among the farmers who are or will be affected by an irrigation project, as well as at the interface of the implementation units and other local water institutions.

Irrigation projects in developing countries, particularly irrigation system management transfer (ISMT) projects, work within the domain of government ministry or ministries and government agencies involved with water resource management, since these ministries and agencies have traditionally controlled irrigation system management. Currents and counter-currents exist in the bureaucratic environment of the water sector of developing countries. Opinions often differ at different levels in the government agencies concerning the feasibility and desirability of an

[1] Director, International Irrigation Center, Research Professor, Department of Biological and Irrigation Engineering, Utah State University, Logan, Utah 84322-4105.

irrigation project. Some government officials will favor a project; some may feel threatened by it or oppose it for other reasons. In many cases, the local feeling in the bureaucratic environment at many levels is that a project is being imposed upon them, and that it is not the one they need for their sector. Some do not consider it feasible due to the effort they may be required to put into it. While in the end many of the local decision makers become convinced by project results of the value of the institutional transformation involved in ISMT, their negative reactions to the transfer project at the beginning can cause serious problems and jeopardize its intended results throughout the life of the project.

Furthermore, the opinions of some levels affect other levels. This stratification of political will concerning a project—its goals and objectives, proposed methods, planned and expected outcomes—can, in addition, induce repercussions, both negative and positive, among the main target population of an irrigation transfer project: the farmers.

In addition, what also complicates the bureaucratic environment and its opinions of a project, whether in favor or against, is the fact that, in many developing countries, two types of irrigation systems coexist within the same country and even within a system—those of the private sector, funded and run by private owners and/or companies; and those of a societal nature, traditionally run by the government but control of which at the district and farm level is now increasingly being turned over to the farmers/water users. While societal irrigation systems and projects aim for water efficiency and increased agricultural production as do the private systems, these societal, government systems also have had a more social goal—that of improving rural life and decreasing political and socio-economic tensions in the rural sector. Thus, these two types of irrigation systems are completely different: they behave differently, have different needs and objectives, and involve government differently.

All these opinions, influenced by the types of irrigation systems involved, affect decisions and actions by government personnel and by farmers after a project is signed for by a top government official and implementation of the project is then attempted. The term “attempted” is used here, because frequently the goals and objectives of the project may become unattainable or may need to be modified if there is not sufficient political will at the levels of government or farmers when it is needed.

POLITICAL WILL IN THE IMPLEMENTATION OF AN IRRIGATION TRANSFER PROJECT

Irrigation system management transfer is a process in developing countries begun in the early 1980s that involves the relinquishment by the government and its agencies of control of irrigation systems at the regional and farm level and the transfer of this control to farmers (water users). Water user associations (WUAs) are organized to assume this responsibility. Sometimes WUAs have been formed by the government before ISMT is initiated, but most often, organizing farmers into WUAs is part of the project.

By its very nature, ISMT involves radical institutional changes, with shifts of power and control. Thus, more than a structurally-oriented irrigation project, or a technologically managerial-oriented irrigation project, an ISMT project that focuses on the institutional aspects of the transfer process can potentially arouse much more opposition.

A frequent scenario seen in irrigation transfer projects involves many layers of political will or lack thereof. Usually a top level member of the government**,** generally a cabinet minister, has signed an agreement and obtained funding for the project. However, the minister does not manage the project. Generally, the director of a water resource agency within the ministry, or a director of a special project-implementing unit within this agency, is responsible for host-country administration of the ISMT project. This implementing-unit director may be appointed by the government, or this position may be created by the international agency that is funding the transfer project. This latter situation in itself often creates friction. Furthermore, this agency/project-implementing unit director may favor or oppose the project, for several reasons. Particularly, if the appointment to directorship depended more upon political reasons than upon technical expertise and knowledge of the irrigated agricultural sector, such a director may be opposed to the project. Political appointees tend to respond to biases of their parties or personal interests and may view any decisions made by the previous government as wrong. Technically-qualified appointees have a greater probability of understanding the goals of the irrigation transfer project.

Political will or lack thereof, continues down the chain of command. Thus, even if the director is in favor, the regional agency branch directors may be opposed or in favor; this situation also often depends on the reasons for their appointment—whether for political or technical reasons. Furthermore, personnel under the regional director within these agencies also form their own opinions; if they are opposed to aspects of the ISMT project, they may transmit this opposition to farmers/water users. Water users—and their WUAs, if they already exist—can in turn favor or oppose the project.

The more the layers of bureaucracy—i.e., positions in the chain of command—the more likely that negative opinions and opposition, with corresponding actions, will be formed.

The ISMT project implementer (company/consortium/university) needs to comprehend the layers and the underlying causes of positive/negative political will involved in the project. This understanding is essential: detecting and managing these layers can be a deciding factor in the success or failure of a project and in the sustainability of the results of the project after the project ends.

CAUSES OF OPPOSITION IN IRRIGATION TRANSFER PROJECTS

Government Personnel

ISMT projects bring great institutional change. For key government personnel at various levels, opposition may arise for several reasons:

- Lack of information about the project and its institutional nature as compared to traditional irrigation projects in the past.

- The expectation that the project will be simply “business as usual” with no upsetting changes; they may react negatively when changes that they view as disturbing or threatening do occur.
- The feeling that a project is being imposed by external forces rather than by those traditionally accepted by the local water bureaucracy; furthermore, feelings against a foreign government, if that government is the main funding agency, can result in increased opinion of a project being imposed, and thus result in greater opposition.
- Circumstantial coincidence of the ISMT project with other national economic reforms affecting government size and positions; the institutional changes resulting from the project add to the stress caused by streamlining and downsizing of the bureaucratic apparatus already being undertaken (USU 2001).
- Misinformation/insufficient analysis of the project’s potential output.
- Anger at being bypassed or slighted in the project agreement.
- Gradients in position, salary, and provision of implementation equipment brought by the project compared to these held by the existing bureaucratic water agency apparatus.
- Different organizations or institutions with overlapping power and/or responsibilities in the water sector of the country—battles of power aggravated by the new ISMT project. Formation of a project-implementing unit to direct project operation and coordination creates such an institution, with parallel and competing powers. Preferential treatment in terms of salary and facilities provided to personnel in this unit creates further inter-institution jealousy and animosity. Thus the government is often not an integrated unit but a fractured one (USU 2002).
- Feeling threatened by the whole ISMT process as management of irrigation systems is taken away from the government and given to the water users.
- Fear of loss of power and financial benefits previously obtained through direct management of irrigation water.
- Fear of loss of positions and income.
- Feeling threatened by the new project management apparatus and technology involved—particularly in more mature personnel.
- Lack of new opportunities and alternatives for traditional personnel and traditional agencies, and the lack of new incentives for mature personnel to update or receive new, alternative training for professional development so as to be competitive in the same organization and other sectors of the administration or elsewhere (Yap-Salinas 2006).

Fears regarding ISMT on the part of many government personnel are often well-founded. ISMT involves institutional restructuring and transformation. The rules of the game concerning power and management, including privileges, change almost completely. At the government level, this restructuring often involves readjustment of roles and/or downsizing. ISMT often causes a jostling—an unpleasant situation with which government personnel in developing countries (unlike the U.S.) are already too familiar, since this often occurs when there is a change of ruling party in the government. Government personnel, especially at higher and middle social and political levels, feel especially vulnerable, and rightfully so, to these changes. ISMT projects make their livelihoods and positions of power even more vulnerable. This effect is aggravated by the fact that, in many developing countries, political instability is endemic. Sudden changes in political power, with changes in position almost all along the chain of command, even in technically-oriented water agencies, are very frequent.

Furthermore, each political change, from top to nearly the bottom, brings a new evaluation of the project and very possibly different opinions, not to mention a learning curve for directors all along the chain concerning the project. Once again, the idea predominates in many developing countries that a project by a previous political party is automatically bad.

Farmers

Political will at the farmer level is also an issue in implementation of an irrigation transfer project, although it is often not quite as disruptive as that in government levels—perhaps simply because farmers have the most to gain by irrigation transfer and are much less threatened by it than government personnel.

However, for various types of farmers, opposition may arise for several reasons:

- The effect of negative political will from mid-level and lower-level regional water agency government personnel. For their own reasons cited above, these personnel may, in an attempt to sabotage the irrigation transfer process, transmit their concerns or malign the project to farmers. These farmers, especially the poorer, less educated ones, can be more susceptible to misinformation. A situation of this type occurred in the Technical Assistance Project implemented by Utah State University in Ecuador in 1997-2001. This transfer project involved training in institutional and participatory management aspects, technological use, agricultural production, marketing, and water resource management, and involved several districts in the central and northern Andean region of Ecuador.

- Local stratification of groups in socio-economic levels and the reaction of large, powerful, entrepreneurial farmers to the transfer process. This is more frequently seen when private sector irrigation coexists with societal irrigation in a given common command area of a system. There are political socio-economic strata, from larger, powerful local farmers with private systems to small farmers on societal irrigation systems. Traditionally, mutual favors take place between the large powerful farmers and the regional government water administrators, at the expense of the less informed, small farmers/users.
  - With a transfer project and its objective of formation/strengthening of WUAs, these large farmers fear losing these perks and preferential benefits, and attempts to capture and command these WUAs may occur.

- Even as the transfer process takes place, the fact is that, as is natural, the more prepared and informed farmers benefit most from project activities and benefits.

- <u>Small farmers' reactions to both the traditional and transfer process situation.</u> Self-appointed local farmer chieftains may accuse the government of implementing just another project to perpetuate the "status quo" and motivate farmers to work against the new institutional transformation.
  - The majority of small farmers, for lack of information and education, react emotionally and are very susceptible to chieftains' efforts to make them "take sides." If the local farmer chieftains are successful, this situation can work seriously against project objectives.
  - This situation can be aggravated by "politicization"—when political parties try to take advantage of this friction. Political parties may try to gain control of the WUA and bend it to their will, with their own political benefit, not with the ultimate benefit of the farmers, in mind (Yap-Salinas 1994). This happened with USU's project in one irrigation district in Ecuador. In the end, the WUA became so politicized, ineffective, and uninterested in training that project involvement with that district had to be terminated (USU 1997-2001).

As can be seen, stratification of reactions for and against an irrigation project can and frequently will occur. Criticism of the project, power grabs, and in extreme cases, sabotage of project activities and derailment of the whole irrigation transfer process may result.

Indeed, the formation of negative farmer opinion is especially damaging if it occurs in the initial project phases, since it is especially the small farmer/water users that the transfer process aims to empower. With a lack of will to work with the goals of the irrigation transfer process, farmers' effective participation in the formation of WUAs, or the participatory development of already formed WUAs, can be seriously affected. This in turn will lead to a loss of many of the benefits of the transfer process—development of participatory decision making, equitable distribution of water, efficient use of water, formation of conscious concern for protection of the natural resources that provide their livelihood, and economy-of-scale ability to invest in the technological modernization and market development necessary to become competitive.

Formation of farmer opposition later in the transfer process, as mentioned, can derail the project or prevent effective continuation and sustainability of project gains.

RESULTS OF OPPOSITION

Lack of political will and opposition to an irrigation project has many far-reaching effects. Indeed, the main result is a "friction factor" in implementing project plans, which can take many forms:

- Delay at several stages of implementation
- Opportunity loss by one o more irrigation district to enter into process
- Holding of funds; delay or stoppage of disbursement

- Delay in paying personnel
- Diversion of project funds
- Denial of necessary equipment stipulated in the signed project agreement
- Removal of key personnel who favor the process
- Endanger the sustainability of the full process in the sector

APPROACHES TO LACK OF POLITICAL WILL AND OPPOSITION IN AN IRRIGATION TRANSFER PROJECT

Project implementers need to be aware of, sensitive to, and concerned with the changes that both government personnel and farmers involved in the irrigation transfer process face—or fear that they face—as a result of implementation of irrigation transfer. They must provide opportunities for these people at all levels to become aware of the true goals and benefits to them of irrigation transfer, to become a valuable part of the transfer process, and especially, in view of many of their well-founded concerns, to continue in new roles in the new “world” of transferred irrigation.

There are many ways to prevent or combat negative political will and aggressive opposition to an irrigation transfer project:

1. Work to develop a well-informed bureaucratic sector, starting with an open forum to present ideas and alternatives. Efforts at the beginning of the project should be directed toward defining a vertical line of command, starting at the upper levels of the administration, in which all government employees involved in the sector adhere to the mission statements and fundamental objectives of the institutional transformation involved in the project. One way to do this is to give all those in opposition the opportunity to express their opinions and criticisms of the process and to try to arrive at a consensus based on democratic interchange of ideas and sound rationale. Furthermore, inviting potential leaders of the farm communities from the irrigation systems to these presentations and debates can be positive in some instances (Carrasco 2004).

2. Specific target-group training of government personnel and farmers. Significant time should be spent at the very beginning of an irrigation transfer project talking not only with government personnel, but also with farmers at all level, listening to their concerns and discussing the goals, objectives, methods, and expected outcomes of the project. Then, as part of the institutional transformation work of the project, specific training should be provided for national and regional government personnel and each group of farmers in a district; this training should focus not only the project, but also on the roles, responsibilities, and benefits for all the participants in the irrigation transfer process.

   Experience has shown that involvement of key national and regional government decision makers and farmers in training about the project’s goals and objectives, methods, and expected outcomes avoids a lot of misinformation, rumors, and development of negative reactions early on (Yap-Salinas 1994, USU 2001).

3. Enable government personnel and farmers to observe successful transfer. One powerful way to prevent a large amount of opposition to the irrigation transfer process from the very beginning is to "preach with example," to show both government personnel and farmers the effects of successful institutional transformation in irrigation transfer, In USU projects, this has been done through interchange of experiences among government personnel and farmers, with those of the area to be newly transferred being enabled to observe successful irrigation transfer in other countries. Farmers, especially, are extremely sensitive to observe the success of others and to replicate observed success. Rather than being told about the history of that successful transfer, they are allowed to observe, analyze, and make their own conclusions and extrapolations to their own possible success. Similarly, regional and local government personnel benefit greatly from observing successful irrigation transfer and from speaking to those who have undergone it. Indeed, seeing has been believing, with remarkable transformation of non-believers in the process to believers and advocates (Yap-Salinas 1995, USU 1997-2001, USU 2001).

4. Work to reduce the number of layers in water national bureaucratic organizations and also attenuate the power of or eliminate altogether overlapping organizations with common water related responsibilities. This is important, because the more layers or overlapping of responsibilities that exist in the water organizations related to the transfer process, the greater the probabilities for development of adverse political will.

   Furthermore, when there are institutions with overlapping water responsibilities and changing this situation is unfeasible, it is helpful to (1) involve these organizations in project information and frank discussion about the project's nature and objectives, and (2) involve key personnel, when possible, in monitoring project activities.

5. Attenuate or reduce the gradients between the project executing units and the rest of the irrigation bureaucratic apparatus in the country. One of the causes of opposition and negative political will toward an irrigation project is the gradients of salary, position, prestige, and equipment perceived by government water agency personnel. It is important that all levels of government personnel feel involved in and have importance in the mission and objectives of the irrigation transfer project.

6. Specifically prepare regional government decision makers for a new role in the post-irrigation transfer world. Because of the great institutional changes that irrigation transfer involves, it is essential to enable these decision makers to envision a new role and new opportunities for themselves: roles as advisors, facilitators, guides to water users and their WUAs in their new roles. These government personnel have education and valuable technical and field experience that water users do not have and to which they truly need to have access. If these government personnel can see that their careers are not ended by irrigation transfer, their opposition will be much less, and indeed, they may come to favor the process.

LESSONS LEARNED ABOUT POLITICAL WILL

Problems in political will and stratification of political will are a reality that must be understood—in general, but also specifically, in each irrigation transfer project. Lack of political will can sabotage a project at any stage, although it is most common at the beginning—and there, potentially the most damaging. However, stratification of political will can be effectively dealt with if it is handled empathetically, energetically, and with care. Indeed, conversion of non-believers in the irrigation transfer process and goals to believers and advocates is essential to the success and sustainability of irrigation system management transfer.

REFERENCES

Carrasco, Silvio (Former Director of the National Institute of Hydraulic Resources, Dominican Republic) (2004). Personal communication.

USU (Utah State University). (1997-2001). Monthly reports on the Technical Assistance Project to the Irrigated Subsector to the Project-Executing Unit (UEP) of the Ministry of Agriculture, Government of Ecuador; to the World Bank, and to Utah State University, Quito, Ecuador (in Spanish).

-----------. (2001). "Transfer of irrigation systems in Ecuador: Final report of the Technical Assistance Project to the Irrigated Subsector," Report to the UEP of the Ministry of Agriculture, Government of Ecuador; to the World Bank, and to USU (in Spanish).

-----------. (2002). *Technical proposal for in-service training program to water users organizations of coastal Peru—PES II.* Presented to the Coordinating Unit of the Irrigation Subsector Project, Ministry of Agriculture, Government of Peru (in Spanish)..

Yap-Salinas, L. H. (1994). *Strategies in the development of water users associations: The On-Farm Water Management Project in the Dominican Republic*, International Center for Self-Governance, San Francisco.

----------. (1995). "Converging factors in the successful transfer of irrigation management responsibilities to water users associations in the Dominican Republic." In *Irrigation Management Transfer: Selected Papers from the International Conference on Irrigation Management Transfer, Wuhan, China 20-24 September 1994. Water Reports 5.* Edited by S.H. Johnson, D.I. Vermillion, and J.A. Sagardoy, International Irrigation Management Institute (IIMI) and Food and Agriculture Organization of the United Nations, Rome, 1995.

----------. (2006). "Continuing education programs for irrigation engineers in developing countries: A pressing need." *Proceedings of the American Society of Civil Engineers World Environmental and Water Resources Congress,* Omaha, Nebraska.

IRRIGATION SYSTEM MANAGEMENT TRANSFER: AN IMPORTANT TOOL FOR DEVELOPMENT OF RURAL SOCIETIES

L. Humberto Yap-Salinas[1]

ABSTRACT

Irrigation provides control over agricultural production not possible under rainfed agriculture, and many developing countries, even those with considerable rainy seasons, use irrigation as a method to improve crop production, especially of export crops. The rural sectors which are involved in this production have generally been characterized by poverty and lack of education. Nevertheless, these sectors represent a large, untapped human resource for developing countries. The focus of development in countries with agriculturally-based economies needs to be not only upon increasing national income through increased crop production, but also upon combating poverty, stimulating education, and improving participation of the rural sector in the national economic and political life of these countries.

Irrigation system management transfer has proved to be one of the best tools for development of the rural sectors of developing countries. Not only is water saved and crop production increased, but through the process, the farmers/water users become empowered to be active participants in management of their water resources and leaders in their communities.

This paper discusses in detail ways that irrigation system management transfer has promoted growth and development of rural societies in developing countries. Methods to encourage and direct this growth of the human factor within irrigation projects, tested through experience in developing countries, are described.

INTRODUCTION

Types of Irrigation Systems

Irrigation systems have long been used worldwide to improve and control agricultural production, even in rainfed areas. Irrigation projects have been undertaken in many developed countries for several reasons, and because of these reasons, there are two main types of irrigation systems in these countries. One is private irrigation systems, similar to those found in the U.S. The other involves irrigation systems undertaken by governments for societal purposes, not just for improved agricultural production.

These two main types are quite different in purpose, operation, decision making, and clients involved. First of all, private irrigation systems, like those in the U.S., are owned and operated by private companies or by big land owners as part of their enterprises; such systems are generally run as an enterprise. The clients are individuals or one or more companies. Decision

[1] Director, International Irrigation Center, Research Professor, Department of Biological and Irrigation Engineering, Utah State University, Logan, Utah 84322-4105.

making is done by the company that owns the irrigation system or by well-informed farmer owners or managers. In contrast, societal irrigation systems are owned by national governments; they are operated by national government ministries and regional government water agencies or, after irrigation system management transfer, they are run by small to medium farmers/users. While improved agricultural production is a key objective, the main purpose of many societal irrigation systems is improvement of rural societies for various political and social reasons. The clients are small and medium rural farmers. Management and decision making has traditionally been done by the government, but now, as irrigation system management transfer takes place in many irrigation districts in developing countries, the farmers who use the water, i.e., the water users, make most of the decisions, particularly at the district and farm level.

The Importance of These Differences for Irrigation Projects

For the company/consortium/ university implementing an irrigation project in a developing country, understanding the differences between these types of projects is essential. Both societal and private projects aim to improve agricultural production and rural life. However, in terms of numbers of users, area, and correlatively, possible volume of water used, the largest proportion of irrigation systems in most developing countries involve societal rather than private irrigation.

Private and societal systems are "different animals." They behave differently; their background and needs are different; the required interactions for improvement of the systems are different; and different approaches are needed. When a contract is made with the government of a developing country for an irrigation project, particularly if it involves institutional transformation, awareness of these differences enables greater success.

WHY GOVERNMENTS OF DEVELOPING COUNTRIES REQUEST IRRIGATION PROJECTS

Reasons for Irrigation Projects

Developing countries face many needs and problems. There are two main reasons why governments of these countries contract for irrigation projects. First of all, most developing countries have agriculturally-based economies; improving agricultural production and exports can improve their economies. Secondly, improving rural satisfaction, while often the main goal of societal irrigation systems, has become pressing in importance in the last century. Rural discontent due to poverty has historically lead to political disruption in developing countries such as El Salvador, Nicaragua, and Peru, to name a few. Keeping the farmer on the land is necessary both for production and for limiting the influx of rural poor to the large cities, where jobs are scarce. Many large cities in Central and South America have seen increased unemployment and crime, particularly as a result of rural unrest and guerrilla movements. Thus these societal irrigation systems often have as their primary goals reduction of poverty, unemployment, rural unrest, and pressures for urban migration. In fact, more than one purpose may be involved when an irrigation system is implemented (Keller 1988).

A Disconnect

However, there has been a type of disconnect concerning the views of needs of developing countries in irrigation. The model for irrigation system management developed in lender/grantor organizations is based on indicators of private sector behavior and goals. This orientation affects the goals and Terms of Reference of irrigation project contracts with developing countries and is often a mismatch for them. Then, implementing these projects becomes difficult because of the differences between private and societal irrigation systems in terms of needs and behaviors involved.

Another disconnect involves teaching in U.S. universities concerning irrigation. This teaching, because of the generally private nature of irrigation in the U.S., is mostly oriented toward private-sector irrigation. Thus many U.S. engineers, as well as international engineers trained in the U.S., bring this orientation to developing countries; when they need to deal with societal irrigation systems, they encounter different goals and focus, different modi operandi, and different priorities.

WATER SCARCITY

One factor that is common to both private and societal irrigation systems is water scarcity. The largest proportion of water is used for farming in both industrialized nations (Dean 2007, National Academies 2007) and developing nations (World Bank Press Review 2006). In fact, it is estimated that 70% of water use in developing countries goes to farming (World Bank Press Review 2006); in fact 72% of Latin America's available water is used in irrigation (Garcés and Mora 2002) and it is expected that worldwide, by 2025, irrigation for agriculture will account for nearly 70% of the water diverted for human use (Merrett 2002). Furthermore, 75% of the world's rural population depends directly or indirectly upon agriculture for survival (Cleaver 2003). However, as population increases and as economies diversify, the need for water for human and industry use increases, and there is increasing pressure to divert water from the agricultural sector to these other uses. Furthermore, for ecological reasons, a certain amount of water must not be diverted. Thus, worldwide, there is an increasing need for more efficient use of water and for a strong, well-informed human resource component to make efficient use of this water.

HOW TO DEVELOP IRRIGATION PROJECTS TO EFFECTIVELY IMPROVE THE RURAL SECTOR IN DEVELOPING COUNTRIES

For any irrigation project being implemented in developing countries, it is essential to:

- Realize the global need for improved water use efficiency and, correlatively, for natural resource conservation.
- Realize that in developing countries, particularly in government-contracted projects, the focus is on societal irrigation. Sometimes in an attempt to resolve social problems, farmers have been moved by the government to areas different from those that they knew, as in the Dominican Republic, where they were moved in the 1970s from a rainfed

environment to a dry, irrigated one (Yap-Salinas 1994a). However, as it happened there, without an effective extension service, farmer/water users often do not know how to manage these systems, nor can they afford the technology to improve water use efficiency.

- Understand the constraints to and situations involved in societal irrigation.
- Realize that if we do not address the issue of building the human dimension, putting effort into building the other dimensions involved in rural development –the technical, economic, resource dimensions (Yap-Salinas 2006)—will be worthless.
- Understand that as a global society facing limitations of vital natural resources, we have to look carefully at who is using the resources and how the resources are being used—as well as where opportunities for improvements are.

Sometimes, for looking at the trees, we do not look at the forest and identify how we can ease resource scarcity and at the same time solve pressing present social and political problems. This often occurs because we ignore those who were granted the privilege of receiving land and water resources—generally small farmers in the irrigated sector of the developing world (World Bank Press Review 2006)—and we as a society do not help them to use these resources properly. Indeed, our failure is not only their loss, but ours as well. There is an urgent need to look at the small farmer of the irrigated sector around the world.

Governments in developing countries have traditionally funded and been responsible for managing irrigation systems. The goals—stated or unstated—of their irrigation systems, and consequently, of any irrigation projects that they contract, focus not only on improving production but also on improving rural societies to meet national socio-political needs.

Many attempts have been made around the world to improve rural sectors in developing nations. There have been sociological studies and many irrigation projects, some with good results. However, rural tensions and problems continue. With increasing water scarcity, there generally have been diminishing returns on investing in big irrigation projects (Ostrom 1992).

Traditional Government Control of Irrigation Systems

In the past, governments managed irrigation systems completely in most developing countries with regional government water agencies executing this control. Irrigation projects had a structural focus: more dams to bring more water to agricultural areas to improve production. Later, with the non-structural approach, irrigation has evolved into a wave of development of managerial skills in the sector, generally implemented through irrigation management projects.

There have been problems with this traditional model of government control of societal irrigation systems. This control has often been inefficient. When the On-Farm Water Management Project was implemented by Utah State University in the Dominican Republic in 1985, one of the problems first noted was the presence of trees in irrigation canals, as well as the poor condition of many canals. Furthermore, water distribution was often inequitable, with farmers further down the distribution system receiving less water. Bureaucratic slowness and red tape have been and continue to be typical obstacles in solving problems in irrigation systems in developing countries. Furthermore, in many developing countries, other pressing national needs—among these, education, health, and political problems such as the need for military funding for anti-guerrilla campaigns or border disputes—have increasingly competed for limited financial resources, and government responsibility for managing irrigation systems at the district and on-farm levels has become untenable. Even further down in priority is recognition of the need for attention to ecological viability of the water systems.

The factor of water scarcity complicates the situation even more for these countries. The need has increasingly been not for more dams, reservoirs, and distribution systems, but for improved management of existing systems (Ostrom 1992). However, as water becomes increasingly scarce, a combination of both approaches may become necessary.

Irrigation System Management Transfer

The movement toward irrigation system management transfer (ISMT, or "irrigation transfer") began in the 1980s in response to the inability of governments in developing countries to adequately administer irrigation systems. Many international funding agencies sponsored projects to promote this transfer of responsibility at the district and farm level from government agencies to the farmers (water users) involved in the corresponding delivery, application, and drainage systems.

This transfer has been achieved by fomenting the formation of water users associations (WUAs) in the corresponding districts to assume this responsibility. Sometimes the governments formed WUAs; sometimes irrigation transfer projects were allowed to form them. Thus some irrigation transfer was done in a "big bang" top-down fashion, sometimes it was done more gradually, with more bottom-up, grass-roots farmer involvement in organizing WUAs (Groenfeldt 1996, Yap-Salinas 1996). Sometimes this transfer was effective, sometimes it was not. When a training component was added, better, more sustainable transition was achieved (Yap-Salinas 1994a, USU 2001).

PROBLEMS OF SMALL FARMERS IN RURAL SOCIETIES

Unlike large private companies involved in irrigated agriculture, small farmers face many problems that limit their progress and often make life in rural societies a cycle of poverty:

- Lack of management skills
- Lack of technology
- Lack of economy of scale and financial resources for investment
- Lack of political and societal clout
- Lack of market orientation—a lack of awareness of and/or lack of access to market opportunities
- Lack of stable, secure markets.

While ISMT projects aim to meet these needs, this last problem, that of stable, secure markets for the small farmers' agricultural production, is crucial. In the end, if the circuit is not closed by providing markets, ISMT is worthless. Stable income is not achieved, and poverty continues in the rural sector.

Traditionally, governments have attempted to confront the problems of small farmers through structural irrigation projects, involving big dam and water distribution systems, or by bringing in technology, but these have generally failed to produce the expected results (World Bank Press Review 2006; Ostrom 1992); particularly in rural areas with large indigenous populations (Uquillas and Eltz 2004).

However, the problem of rural agricultural societies in developing countries is the need to recognize that building the human dimension is a primary factor in rural development, in water efficiency, in improved resource conservation, and in rural society sustainability (Yap-Salinas 2006).

Training: The Key

Small farmers generally lack educational opportunities as well as the many other skills and opportunities listed above. Extension services as known in the U.S. generally do not exist for small farmers in developing countries. Thus, for irrigation system management transfer to be effective, these farmers must be empowered to take charge of their irrigation systems effectively. Participation in WUAs is not enough; they need knowledge (Hawkins 1996).

Farmers need training in the following areas:

- Managerial skills
  - Participatory management
  - Equity in water distribution
  - Institutional knowledge and innovation
  - Natural resource management and conservation
- Technical skills:
  - O&M of irrigation systems
  - irrigation scheduling
  - use of technology
- Production
  - Agricultural techniques
  - Step-wise introduction of technology
- Market orientation and management
- Access to capital and credit on fair terms
- Effective organization for common goals and needs.

Various transfer projects around the world have addressed these needs. Utah State University's On-Farm Water Management Project (OFWMP) in the Dominican Republic and its Technical Assistance Project (PAT) in Ecuador are two such projects. The OFWMP involved two irrigation districts: one in a very poor, arid area originally brought under irrigation for societal reasons; the other in a rainfed, less poor area. The PAT involved seven very distinctly different irrigation districts in the central and northern Andes: two with almost purely indigenous farmers;

two with a mixture of small farmers and large, entrepreneurial, market-oriented farmers; and three with a mestizo population and composed of small-to-medium-sized farmer tenants. Some of these PAT districts were at high altitude, some at warmer, lower altitudes. Both projects involved training and chaperoning of water users in the organization of WUAs, and participatory decision-making and economy-of-scale negotiation of markets, as well as meeting all of the above training needs (USU 2001, Yap-Salinas 1994b).

Indeed, as well as in the experience of Utah State University in the Dominican Republic and Ecuador (Yap-Salinas 1994a, 1994b; USU 2001), training using participatory methods has been effective elsewhere, as in Indonesia (Feder, Murgai and Quizon 2003).

ADVANTAGES OF IRRIGATION MANAGEMENT SYSTEM TRANSFER FOR RURAL SOCIETIES

Several advantages have been observed in the rural societies involved in irrigation system management transfer in the OFWMP and PAT of Utah State University.

1. <u>Unity around a common need and resource: Water</u>

Water, the life-source for agricultural production, is essential to the income of rural societies, particularly of small farmers. When farmers are given the opportunity to ensure equitable distribution of this increasingly scarce resource, they become eager to do so. Water management becomes the centerpiece of rural life, and the WUAs often become the most important organizations in these rural societies. Participation in their WUAs enables farmers to effectively and efficiently handle the water resources that are so vital to their survivability.

2. <u>Through formation of WUAs, organization for common goals</u>

Farmers (water users), through their WUAs, can manage common goals involved in their agricultural production. These goals include:

- Equitable distribution of water
- Economy-of-scale to obtain needed technology
- Legal status to negotiate contracts
- Political force to work with the private sector and to avoid abuses of the past of small farmers. Such abuses have included, to name a few, the inability to obtain credit and the bending of government water decisions to favor large farmers and agribusinesses.)
- Obtaining markets and managing marketing through scheduling of production
- Access to capital and credit on fair terms.

3. <u>Improved water use efficiency in the face of increasing national water needs and increasing water scarcity</u>

As farmers learn to manage their irrigation systems, use irrigation scheduling, institute appropriate O & M, institute and enforce water tariffs for water use, and gradually, through economy-of-scale organization and increasing income, obtain needed technology, they improve the efficiency of water use. This benefits not only their own rural societies, but the nation as well in its allocation of water resources.

4. Supporting the cost of the use of water resources

Until recently, because of their traditional dependency upon the central government, rural societies have not been accustomed to paying for the services and infrastructure needed to deliver water to them. As farmers learn to pay, often in a stepwise approach that they can afford, water tariffs for their water use and corresponding water services, they begin to appreciate the scarcity and value of water, and the need to better manage this precious resource.

5. Awareness of need for and ability to effect greater preservation of the natural resources that provide their livelihood

As farmers and their families learn to manage their water distribution systems, and as their incomes increase through increased agricultural production, they become less concerned about basic survival and are actually enabled to become aware of the need to preserve their natural resources, not only for themselves, but for their children and future generations. This concern is a type of more abstract concern on Maslow's pyramid of needs that they can attend to only after their more basic needs for food and shelter have been met (Maslow 1970).

6. Development of participatory democratic principles through education and actual need to use these

In many developing countries, participatory democratic principles have not been a part of the people's historical background or personal experience. Particularly in rural societies that subsisted in irrigation districts built as part of a societal irrigation system and managed by government bureaucracies, participating in control of something that so intimately affects their lives and livelihood is a new experience for most farmers. As farmers learn participatory principles through training in irrigation transfer projects, they become aware of the benefits of becoming informed and choosing wisely when making their decisions. In the experiences of the OFWMP in the Dominican Republic and the PAT in Ecuador, these WUAs have catalyzed rural communities to become involved in decision making of issues concerning them (Yap-Salinas 1994a, USU 2001); such issues include, within the system, equity between large and small farmers; and outside the system, the need to negotiate marketing and processing with intermediaries. This approach of "democracy in action" is achieved in practice and is no longer an esoteric concept.

7. Negotiating capacity and influence: power in numbers

Through forming their WUAs and obtaining legal status of these organizations, water users have increasingly found an economy-of-scale that increases their power in negotiation in their market environment and in their business dealings. Similarly, through their WUAs, they command political clout in getting their needs heard; they become able to deal with the central government in matters such as obtaining legal recognition and access to capital (USU 2001). Indeed, federations of WUAs can influence ministry decisions, as has been seen in the Dominican Republic and Ecuador in years following termination of the OFWMP and PAT.

8. Ability to seek extension service and improved technology

Through their WUAs with legal status, water users can demand effective extension service from the governmental water resource agencies; or they can, through their water tariffs, increasingly afford needed technological improvement and become buyers themselves of technology for their agribusiness enterprise.

CONCLUSION

Unlike previous, structurally-oriented irrigation projects that built dams, reservoirs, and distribution systems; and unlike other projects that provided technology, ISMT projects focus largely on the human dimension in transfer—on developing the managerial and participatory abilities of the water users, and then on their use of technology and agricultural production techniques to increase agricultural production and efficiency in water use. Thus, institutional transformation in the irrigation transfer process, through its work with water users, develops human capital, providing a missing link, not addressed in previous projects, in promoting success and sustainability in irrigation and stability in the rural sector.

Furthermore, ISMT, through its organization and strengthening of WUAs and its development of human capital, offers a new launching platform for real development in the rural sector.

Irrigation system management transfer is one of the best tools for rural society development in developing countries because it addresses the need for building and strengthening the human dimension in development. While human resource development is an intangible, hard-to-quantify item and may not show up in rates of returns for a project—and therefore may be overlooked as a valid goal and valuable result of a project—the need for human resource development must be met, because it, in turn, meets the needs of these countries for improved water efficiency, improved natural resource conservation, and improved rural stability—results that indeed are quantifiable. For the rural societies themselves, ISMT brings opportunities for personal and society development and improved income. It reduces farmers' flight to the cities, where life as uneducated, unemployed people is even more desperate. Above all, it brings realistic hope for a better life to the people in these rural societies.

REFERENCES

Cleaver, K. (2003). Information from *Il Manifesto* (Italy, Feb. 22, 2003), in World Bank Press Review: Headlines for Wednesday, February 26, 2003: Agriculture and poverty. <newsbureau@worldbank.org>.

Dean, Cornelia (2007). "That 'drought' in Southwest may be normal, report says," *New York Times*, Vol. CLVI, No. 53,863. February 22, 2007. A13. <http;//www.nytimes.com/2007/02/22/us/22river.html> (accessed February 24, 2007).

Garcés, C., and Mora, L.A. (2002). "Water for food security and rural development in the South American context." *INPIM (International Network on Participatory Irrigation Management) Newsletter (World Bank)*, 12, 11-13.

Feder, Gershon, Rinku Murgai, and Jaime B. Quizon (2003). *Sending farmers back to school: The impact of farmer field schools in Indonesia.* World Bank Policy Research Working Paper 3022. Washington D.C.: World Bank Institute, World Bank.

Groenfeldt, David (1996). "Gradualism or big bang?" *INPIM Newsletter*, No. 2., March 1996, 4.

Hawkins, Jr., Robert B. 1996 "Delivering sustainable development," *Self-Governance* (International Center for Self-Governance: San Francisco, California), Spring 1996, 1.

Keller, Jack (March 1988). *Irrigation scheme water management*, WMS Professional Paper 4. Logan, Utah: Utah State University, 5.

Maslow, A. H. (1970). *Motivation and personality* (2nd ed.). New York: Harper and Row.

Merritt, Stephen (2002). *Water for agriculture: Irrigation economics in international perspective*, Spon Press, New York.

National Academies (2007). "Report in brief: Colorado River Basin water management: Evaluating and adjusting to hydroclimatic variability." <http://dels.nas.edu/dels/rpt-_briefs/Colorado_river_management_final.pdf> (accessed Feb. 24, 2007).

Ostrom, Elinor (1992). *Crafting institutions for self-governing irrigation systems*. San Francisco, California, U.S.A.: International Center for Self-Governance, Institute for Contemporary Studies Press.

Uquillas , Jorge E. and Melanie A. Eltz (2004). "The quest and practice of indigenous development," *Lessons of indigenous development in Latin America: The proceedings of a World Bank workshop on indigenous peoples development,* LCR Sustainable Development Working Paper No. 20. Washington, D.C.: World Bank. <http://wbln0018.worldbank.org /LACLAC.nsf/ECADocbyUnid/C16A758627B47FAD85256F630064BEA3?Opendocument> (Accessed Feb. 28, 2007).

USU (Utah State University) (1997-2001). Monthly reports on the Technical Assistance Project (PAT) to the Irrigated Subsector to the Project-Executing Unit (UEP) of the Ministry of Agriculture, Government of Ecuador; to the World Bank, and to Utah State University, Quito, Ecuador (in Spanish).

-----------. (2001). "Transfer of irrigation systems in Ecuador: Final report of the Technical Assistance Project to the Irrigated Subsector," Report to the UEP of the Ministry of Agriculture, Government of Ecuador; to the World Bank, and to USU (in Spanish).

Yap-Salinas, L. H. (1994a). *Impact of the On-Farm Water Management Project on irrigation policy in the Dominican Republic*, International Center for Self-Governance, San Francisco.

----------. (1994b). *Strategies in the development of water users associations: The On-Farm Water Management Project in the Dominican Republic*, International Center for Self-Governance, San Francisco.

----------. (1996) “Neither gradualism nor big bang, but easy does it.” *INPIM (International Network on Participatory Irrigation Management) Newsletter (World Bank)*, No. 3, July 1996, 8-10.

----------. (2006). “Essential dimensions and elements in the design of irrigation system management transfer projects.” *Proceedings of the American Society of Civil Engineers World Environmental and Water Resources Congress*, Omaha, Nebraska.

World Bank Press Review. 2006. “Headlines for March 20, 2006: World’s water problems, and solutions, can be found on the farm.” <newsbureau@worldbank.org>

SOCIO-ECONOMIC INTERACTIONS AMONG MULTIPLE USES OF WATER IN HIMACHAL PRADESH-INDIA

A.K. Randev[1]
Uma Randev[2]

ABSTRACT

'Water' the most essential input in bio-world has relatively been becoming more scarce with an increasing number of its users and uses. There is no absolute scarcity of water only the relative scarcity exists due to improper management practices while putting water to various uses. This paper has been developed with objectives (i) to highlight availability of water and its' different uses at existing level of use (ii) to find out gaps between supply of and demand for water among competing uses with emphasis on irrigation and drainage (iii) to suggest remedial measures for improving interactions of irrigation and drainage systems with psycho-socio-economic parameters in the light of environmental considerations. An economic analysis of getting economic optima through maximum sustainable yield and scoring technique reveals mainly productivity levels of food crops 4-5 times less than global levels. Although State receives, on the average, 152cms of rainfall and has many rivers, tributaries and lakes, yet only 20 per cent of total cultivated area has been found to be irrigated. The most of area in the State faces deficient rainfall by –20 to –59 per cent of the normal, leading thereby to low productivities in agriculture from small holdings (1.2 hectare). The State consumes about 92 per cent of utilizable water in agriculture and remaining portion in other uses like power generation, industry and domestic. The demand for water amongst these uses has been found to increase by about 3 to 4 times in the next twenty years, therefore an increase in gap between supply of and demand for water has been observed in future. Interactions among psycho-socio-techno-economic parameters reveal individual's attitude towards developmental efforts in water related projects which should be imaginative and creative on technical lines.

INTRODUCTION

Economist John M. Keynes idea of 'man's success is his failure too' holds true, in case any environmental parameter during developmental activity shows reverse trend in relation to it's natural existence. In simple words, economic development exhausts natural resources and over exhaust leads to environmental degradation. Hence, a balanced approach between use and regeneration of renewable resources has been observed to be followed either to stop or reduce environmental degradation. It has also been observed that during yester years of planning, degradation of natural resources in developing countries has increased immensely due to increasing number of 'users' of these resources. A dire need has been felt to make judicious use

[1] Associate Professor (Agril. Econ.), Dr. YSPUH & F, RHRS, Mashobra, Shimla-7, H.P.-India V.F. Division WRE, AIT (Sept. 1992), Bangkok, Thailand. INCID member to ICID WG on ON- Farm Irrigation Systems. 0091-177-2640434, Fax: 0091-177-2740793, E-mail randev26@rediffmail.com
[2]Head, Department of Psychology, Rajkeya Kanya Maha Vidayalya (RKMV), Longwood, Shimla-1 H.P. – India, 0019-177-2640434, randev15@rediffmail.com

of these resources – most importantly 'water'- the most essential input in bio-world which has relatively been becoming more scarce with an increasing number of it's users. Although there is no absolute scarcity of water as nature has blessed this earth with plenty of water, yet the relative scarcity has been observed only due to improper management practices while putting water to various uses.

India the 7th largest country in the world accounts for a meager 2.4 per cent of the world surface area and supports 16.7 per cent of the world population. It has been found that average annual exponential population growth rate of 1.95 per cent (2001), has been putting more pressure on meager land and other natural resources (Ruddar Datt et.al. 2007). This is clear from the fact that per capita availability of water at national level has reduced from about 5177 m^3 in 1951 to the estimated level of 1820 m^2 in 2001 i.e. by 65 per cent (Anonymous, 2007). Similarly, acute water shortages have been experienced year after year by most parts of the country even by those parts where sufficient rainfalls occur. Albeit emphasis has been given to integrated water resources development and management for optimal and sustainable utilization of the available surface and ground water in the National Water Policy, yet shortages have been found to become more and more severe.

Himachal Pradesh located between $30^0$22' and $33^0$12' N latitude and $75^0$47' and $79^0$4' East latitude comprising of 4 agro climatic zones with an attitude range 350-7000 meters above mean sea level receives 180 to 3000 mm of rainfall. In spite of good rainfall about 20 per cent total cropped area is irrigated and the problem of water scarcity has been assuming crisis proportions with growth of cities and increasing urban/rural population leading thereby to rising demand for water for irrigation, domestic consumption, power supply, industrial use, and navigation etc. Knowing the fact of inelastic supply of water from 'nature' and elastic demand for water from its' users side, role of management of water resource use in the light of economic principles becomes imperative, hence a strategic approach to highlight gaps in the water resource use and availability has been adopted in this paper.

OBJECTIVES

This paper has been developed with the following specific objectives:

(i) To highlight availability of water and its' different uses at the existing level of use,

(ii) To find out gaps between the supply of and demand for water among competing uses with emphasis on irrigation and drainage and,

(iii) To suggest remedial measures for improving interactions of irrigation and drainage systems with psycho-socio-economic parameters in the light of environmental considerations.

MATERIALS AND METHODS

Sample has been drawn from Shimla district by adopting purposive and multi-stage stratified random sampling. The size of sample has been 100. Data collected from primary and secondary sources were analyzed for objective (1) & (2) by calculating weighted averages, multiple responses and by using law of equi-marginal utility i.e.

$MU_{w1/P1} = MU_{w2/P2} = MU_{w3/P3}$ ---------------------$MU_{wn/Pn}$

Objective (3) has been analyzed by adopting natural system assessment with economic valuation methods through scores. To find out interactions of irrigation and drainage with socio-economic parameters flow diagram has been used:

* Proper Irrigation →	Increase in Productivity →	Upgradation of other Socio-ecnom-. mic parameters →	Reduction in Poverty------> more confidence	

* Proper Drainage →	Avoidance of wastage of water, funds & floods →	Multiple uses of water →	Building healthy environment

Figure 1. Map of the study area

For interpretation of impacts all environmental indicators were arranged into a simple matrix. Putting a slash in box, magnitude was indicated as 1,5, 10 as least, moderate and greatest on left hand side of slash and importance as 1, 5, 10 low, medium and high on right hand side. To prioritize beneficial and adverse impacts from farmers' stand-point weighted numbers were calculated.

RESULTS AND DISCUSSIONS

Water Availability Situation at National and State level

The annual water availability of the country has been assessed on the average as 1869 billion cubic meters (BCM). The total surface water and ground water out of this total utilizable water have been found to be about 37 and 23 per cent respectively and the remaining about 40 per cent evaporates and percolates into the soil (Anonymous, 2007). Thus, only about $1/3^{rd}$ and $1/4^{th}$ of the total annual water available can be put to use which is available in the form of surface and ground water respectively. However, quantity of water which evaporates has also been found to play an equally important role in maintaining hydrological cycle.

In the light of rising population, the Indian planners have made expansion of irrigation facilities as the main part of the strategy for increasing food production so as to feed increasing population. The irrigation potential in India has increased through major (Culturable Command Area > 10.000 Ha), medium (2000-10,000 Ha) and minor (< 2000 Ha) irrigation projects (2004-05) i.e. by 337 per cent upto tenth plan period. Similarly with increasing hectarage, expenditure incurred has also increased by 347 per cent during the same period. Proportionately similar increasing trend in hectarage and expenditure incurred has been found in the state of Himachal Pradesh. Consequently net irrigated area in the state has increased by 24.33 per cent during a decade 1990-2000, which has lead to an increase in productivity of food crops in irrigated area (Anonymous 1992 and 2001). Revenue data have revealed an increase in area under cash crops like fruit crops, vegetables and flower crops as is evident from Table 1.

Table 1 shows although total cropped and net area sown have declined by 2.80 per cent and 5.68 per cent respectively, yet area sown more than once has increased by 1.12 per cent which shows an inclination of farmers towards growing of vegetables and flower crops thereby brining shift in the cropping pattern. Continuous efforts of government through irrigation expansion schemes

Table 1. Land Use of the State showing Area under Cash Crops and Net Irrigated Area

Sr. No.	**Particulars**	**1990-91**	**1999-2000**	**(,000 Ha Decadal variation (%)**
1.	Total geographical area	3367.60 (100.00)*	4531.80 (100.00)*	34.57
2.	Net area sown	582.80 (17.30)	551.50 (12.20)	-5.68 -(29.50)
3.	Area sown more than once	400.80 (11.90)	405.30 (8.90)	1.12 -(25.20)
4.	Total cropped area	983.60 (29.20)	956.80 (21.80)	-2.80 -(27.70)
5.	Area under vegetables	27.00 (approx,)	49.86**	84.00
6.	Area under fruits	180.00 (approx.)	200.20**	12.00
7.	Net irrigated area	99.46	123.66	24.33

*Figures in brackets show percentages to the total.
** Figures as per 2005-2006.

like the pattern of accelerated irrigation benefits program on loan (90 : 10) the Central loan assistance released in 2004-05 comprised of $0.08 million loan and $0.80 million as grant in a total of $0.88 million; National Project for Repair, Renovation and Restoration of Water Bodies directly linked to Agriculture at an estimated cost of $0.71 million in 14 states including H.P. in the ratio of 3 : 1, thereby with share of Centre of $0.24 million have made diversification of crops possible and availability of water for domestic purposes. Similarly, Table 2 shows stage of Ground Water Development 58 per cent, over exploited blocks where annual ground water extraction exceeds annual replenishable resource have been found to be about 15%, followed by semi critical (70-100% extraction) as 10% and critical (90-100%) as 0.50%. Thus about half of the half ground water extraction has been found to be at more than 70% of extraction stage, therefore, continuous research and development needs to be continued so as to make use of underground water more judiciously. In the similar process of development, scientific efforts have proved the extraction possible at an elevation of about 3000-4000 meters above mean sea level in the dry temperate zone of the state of H.P. Hence with on-going scientific efforts demand for and supply of water have been moving in the same direction. Will a man be having a balance between the two ?

Similarly governments have been making all round efforts to increase supply of useable water through national and international level Boards, Councils, Commissions and Co-operatives etc. by exchanging technical knowledge and strengthening funding structure. Alongwith irrigation , energy sector and other uses of water, have been developed . Government has also enacted various laws to proctect environment' like Water Prevention and Control of Pollution Act 1974 which lays down specific standards for discharge of waste water; National River Conservation Plan 1995, so as clean rivers of the country etc.

Table 2. Ground Water Availability and Utilization

Sr. No.	**Particulars**	**Area BCM**
1.	Annual Replenishable Ground Water Resources	433
2.	Net Annual ground water availability	399
3.	Existing Ground Water Draft	231
4.	Stage of Ground Water Development (%)	58
5.	Total Blocks	5723
6.	Over exploited Blocks(839 No.)	15%
7.	Critical (90-100%) (26 No.)	0.50 %
8.	Semi critical (70-100%) (550 no.)	10%

Water Utilization at Macro level

Multiple uses of water can be serially and priority-wise arranged as domestic (food and drinking), agriculture, industry, power generation, navigation etc. It has been estimated that 92 per cent of the total water utilization is used in irrigation sector and the remaining 8 per cent is put to other uses. With elastic demand for water on account of more number of 'users' and uses in future and inelastic supply of water, need' of management principles in water-use becomes very important.

Villages in Himachal Pradesh have been provided with the facility of drinking water as over 13000 hand pumps have been installed in the state upto 2006. The state has also taken up a drinking water cum irrigation scheme with the total cost of $71 million with the Gesellshaft for Technische Zuoammeuorbeit (GTZ). A water supply scheme worth $9.5 million has been launched for Shimla town in the light of huge demand for water throughout the year due to huge rush of tourists and local population pressure. The govt. of India has approved 471 schemes of

$17 million under Swajal Dhara Programme and 49 small scale irrigation schemes of $3.8 million have been sanctioned by central government to supplement irrigation and drinking water supply. Being a hilly state, government has been making all round efforts to explore hydro power potential. Five river basins namely Chenab, Rabi, Beas, Satluj and Yamuna which emanate from comprises of expeditious actualization of the hydro-electric potential and introduction of power Western Himalayas pass through the State. The strategy of development in the power sector

sector reforms to bring efficiency in the sector and provide high quality power to the consumers at reasonable rates besides availability of abundant power to industrial and tourism sectors. The total identified potential in the state has been estimated to be 21000 MW which has been found to be one fourth of India's total hydro-power potential. Out of this 6067 MW (28.90%) has already been harnessed till 2006 by various agencies. Projects aggregating to 7602 MW (36.2%) are under execution. The state has progressed specificity in developing hydro-power consequently all the census villages (100%) in the state have been electrified.

Thus, government of the state has been trying to increase supply of water through various projects so that water utilization among various uses is increased.

Gaps between Supply of and Demand for Water at Micro level

Out of the total geographical area of 5.6 million hectare, area of operational holding is about 1.0 million hectare owned by .86 million farmers. Average size of holding has been worked out to be 1.2 hectare. Agriculture being the main occupation of the people of Himachal Pradesh, provides direct employment to about 71 per cent of the main working population. With average size of family i.e. about 6 persons per household, about 70-80 per cent of the total population has been found to be directly dependent upon agriculture sector, in which the 'role' of water needs to be further emphasized.

Data have revealed dominance of fruits cultivation in the state in over-all agriculture sector, hence water availability and demand for water has been worked out for 1.2 hactare piece of average holding size under the presumption that all farmers having only apple plantation in one hectare and 0.20 hectare is having house, livestocks, and store/ shed etc. The multiple uses of water have been prioritized on the basis of needs of users/farmers/orchardists by using law of equi-marginal utility. Hence, demand for water has serially been worked out (i) for domestic use and (ii) irrigation. The study area receives, on the average, 1100-1300 mm annual rainfall and in spite of this farmers/orchardists have to depend upon rains for better crops as about 80% area is rain fed. Thus balance between demand for and supply of water needs serious view. Table-3 shows demand for water for domestic purposes including washing/bathing, sewage, cooking, drinking etc. and irrigation purpose for fruit plantations.

Domestic consumption shows, major share of water has been found to be used cumulatively in toiletary and washing and cleaning i.e. about 43 per cent followed by bathing (40%) and food and drinking (17%) per house hold on per annum basis, thus a household has been found to consume 0.108 million litres of water for domestic purpose in rural area. Same level of consumption has been found in urban areas. Irrigational requirement for one hactare piece of land growing apple has been worked out to be 0.241 million litres.

Table 4 shows supply of water per household on per hectare basis. Table 4 reveals further that on account of developmental efforts in expanding irrigation, 80 per cent gap still exists and in domestic use also 67 per cent availability needs to be developed on per household basis in the rural area. Over-all, 76 per cent gap between demand for and supply of water has been found to be filled up by making developmental efforts on the basis of research based data.

Table 3. Domestic consumption and irrigational requirement of water at the orchard

Sr. No.	Particulars	Water requirement (Per family of average size = 6 persons	Percentage
1.	Bathing(litres)	120	40
2.	Toiletary(litres)	60	20
3.	Food & Drinking(litres)	50	17
4.	Washing & Cleaning	70	23
5.	Total	300	100
6.	Perhousehold/annum(million ltr)	0.108	
7.	Irrigation for one Ha plantations = 336 no. of plants For a period of 4 months(lakh litres/annum) excluding rainy & snow season	0.241	
8.	Grand Total (million ltrs)	0.349	

Table 4. Supply of Water per Household

Sr. No.	Particulars	Demand for water (D)	Supply of Water (S)	Gap between (D) & (S)
1.	Domestic (lakh litres)	1.08	0.36	0.72
2.	Agriculture/Horticulture(Rainfed-Flood)	5.00	1.00 (20.00)	4.00 (80.00)
3.	Agriculture/Horticulture(Drip)	2.41	0.48 (20.00)	1.93 (80.00)
4.	Total	3.49 (100.00)	0.84 (24.00)	2.65 (76.00)

Glaring facts have been inferred that in spite of good rainfall, at first, a household has to suffer from water scarcity at least for 4 months in a year due to improper management/channelization/ distribution of water in rural as well as urban areas. Secondly about 70% rainfall occurs during summer monsoon within a period of maximum 3 months (June-July to Aug-Sept), so a need has been felt seriously to channelize rainwater.

Consequences of Gaps

The state receives, on the average 1520 mm of rainfall and has privilege of snow-fed 8 major rivers and tributaries, 18 natural lakes, and 4 man made lakes, yet only 20 per cent of the total cultivated area has been found to be irrigated. Due to dwindling environmental and weather parameter like deforestation, soil erosion, floods, varying temperature conditions and humidity levels, untimely rains/snow/hails etc. have further lead to natural resources degradation, consequently state has been facing deficient rainfall by –20 to 50 per cent of the normal, leading thereby to low productivities in agriculture. In apple orchards too irrigated orchards have been found to yield about 30 per cent higher yield on per hectare basis as compared to rain fed orchards.

The state consumes dominant share i.e. 92 per cent of utilizable water in agriculture and remaining portion in other uses like power generation, industry and domestic. At present level of water use among basic and competing it has been found that water has not been managed properly to bring equality between demand and supply, whereas demand for water among these uses has been found to increase by about 3 to 4 times in the next 20 years. Thus a further increase in gap between supply of and demand for water unfolds disastrous negative environmental impacts.

Magnitude and Importance of Environmental Parameters

Interactions of irrigation and drainage system with psycho-socio-economic parameters have been found to prioritize effects of water resources on environment. As impact of irrigation on crop yield worked out by using yield equation (Randev, 2005) has shown 2.3 times more productivity from a piece of land if required number of irrigations are given at right time to a crop. 100 per cent respondents have reported here positive effects of irrigation leading ultimately to upgradation of psycho-socio-economic parameters and reduction in poverty(Table 5 & 6). Table 5 further reveals, proper drainage avoids wastage of water which can be put to multiple uses in a cyclic manner. Adoption of technology in the form of new varieties and new techniques of water harvesting has been reported by 76 % of the respondents.

Water resource has been considered as firstly, affecting each parameter, simultaneously, at the time of its occurrence as a natural event, although degree of its action varies and secondly each parameter is complementary to another and moves in a single direction. Table 6 clearly shows (rank-wise) that the prime objective of the farmer is to maximize net income. All other components of economic indicator have been found at the existing level of farm resources, confined to local environment, thus all will rise with adequate irrigation. Literacy has been considered to be an expediting force of all the technologies and its level and significance, like other social indicators, is limited as it is near to moderate, although its magnitude is at macro level. The fertility of soil has been found to be low and need to be considered at unit level. Rainfall, temperature and humidity have high significance but presently causing disastrous effects on ecology of each location in the study area. The new technology and awareness about other attitudinal parameters related with religions also have high significance but magnitude has been rated low. Technology has the greatest significance but needs to be brought at the door-step of each holding.

Remedial Measures

Availability of water resource directly through rains and indirectly through irrigation projects accompanied by above facts and efforts suggest farmers' psychological, social and economic values on the top, because these form the base on which location-wise demands can be found out for ensuring scientific conservation and distribution measures of water from the surplus areas to the deficit areas through networking of water channels. At the same time, development of urban areas should be in harmony with the demand for and supply of resources schedule of rural areas. Thus for a balanced approach development of water resources among competing uses needs to be adopted as shown by a sequential process (S1):

Water resource potential at a particular location → Demand for water in various activities/uses-wise → Number of users to be covered → Technicalfeasibility → Distribution/supply on technical grounds in harmony with topography of the place,

S1 Flow Diagram showing balancing of 'D' and 'S' from the Source to the Using areas.

Table 5. Socio-economic characteristics of the study Area.

Sr. No.	Characteristics	Unit	Pooled
1.	Social		
	i) Sample size	No.	100
	Marginal	%	16
	Small	%	29
	Medium	%	29
	Large	%	26
	ii) Family size	No	6
	iii) Literacy	%	77
2.	Economic		
	iv) Land holding (state average)	Ha	1.20
	v) Area under orchard	Ha	1.00
	vi) Irrigated Area	%	20
	vii) Cropping intensity	%	100
	viii) Yield of apple/ha	tones	5.6
	ix) Benefit cost ratio	Rs.	1:2.52
	x) Net income(lakh)	Rs.	1.81
3.	Awareness		
	ix) Degradation of natural resources	%	100
4.	Problems		
	xii) Irrigation	%	100
5.	Adoption of Technology		
	Modern	%	76
	Traditional	%	24

In rural as well as urban areas, water harvesting has been found to play a very important role. It has been found that on an average family of 6 persons at least 50 per cent of the water requirement of 4 months in a year can be met out if roof harvesting is done (Fig. 2). At least 43 per cent water used in toiletry and bathing can be made available to one self through roof tops by constructing suitable location specific structures as a part of construction of the entire house and this can supplement the water requirement of the family, already met through public distribution system.

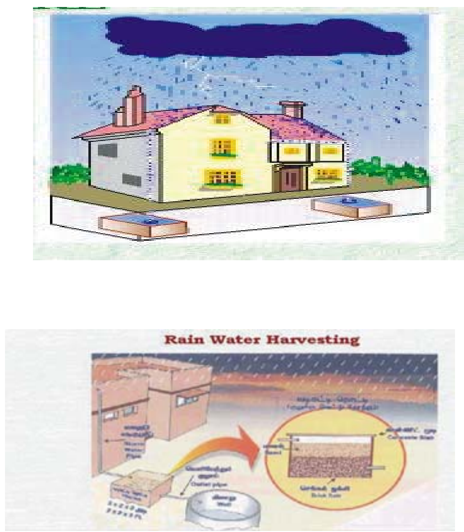
Table 6. Magnitude and Importance of Environmental Parameters in Water Resource Use.

Sl No.	Indicators	Nos. (Weighted)		Sl. No.	Indicators	Nos. (Weighted)	
		M*	I*			M*	I*
1.	Social				(xv) Soil moisture	2	4
	(i) Employment	4	5		(xvi) Floods	9	6
	(ii) Literacy	9	7	4.	Attitude		
	(iii)Communication	7	5		(a) Traditions		
2.	Economic				(xvii) Worship implements	3	3
	(iv)Land use	2	3		(xviii) Carry operation with holy time	3	3
	(v) Cropping intensity	5	4		(xix) Success depends on God	2	8
	(vi)New technology	10	8		(xx) Optimists more successful in business	3	7
	(vii) Yield of crop	3	4		(b) Technology		
	(viii) Net Income/ha	5	3		(xxi) Use of new varieties	4	8
	(ix) Benefit cost ratio	2	2		(xxii) Use of insecticides/pesticides/weedicides	4	8
3.	Awareness about Natural Resources				(xxiii) Follow recommended practices	3	9
	(x) Rainfall	9	8		(xxiv) Awareness about new developments	5	8
	(xi) Temperature	9	7	5.	Others		
	(xii) Humidity	5	6		(xxv) Credit facility	5	5
	(xiii)Soil erosion	8	7		(xxvi) Marketing Management	4	7
	(xiv) Soil Fertility	3	2				

M*shows Magnitude I*shows significance of environmental parameters

This water harvesting system from roof top needs to be joined with public distribution with suitable connections of individual lay outs as bigger water harvesting and storage structures need to be built by Government for further distribution at the time of scarcity. This has been observed due to the fact that individuals have a constraint of land and funds and one can construct a structure of certain limited capacity only.

Figure 3 highlights India's rural water harvesting practices in different directions of the country. This can safely be inferred from both the figures that if rains channelized from surplus (nature) and deficit (rural/urban areas) equilibrium position can be achieved. Both figures also reveals need of evolving workable location specific and cost effective designs of water harvesting



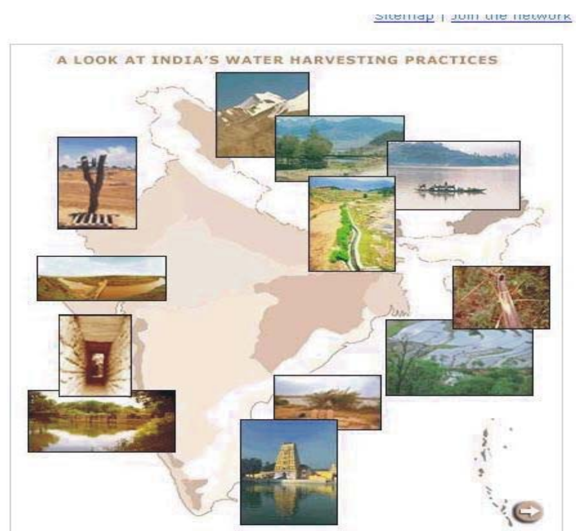


Figure 2. Water Harvesting through roof tops. Figure 3. India's water harvesting practices

structures in rural as well as urban areas to minimize water scarcity position. For stricter implementation, it has been observed that Government should make such designs mandatorywhich benefit saving of precious water, avoidance of floods and funds paid for compensating floods.

Interaction among psycho-socio-techno-economic parameters reveal individual's attitude towards developmental efforts in water related projects, which should positive, imaginative and creative that should be strengthened by publicity through awareness camps by involved agencies to aware about the finiteness of water in the long run as opined by 100%. Thus motivation through full package has been considered to be required. Demand for water at a particular location in rural/urban areas for most urgent needs priority wise, can be met out by technical lay out of water harvesting structures so as to distribute water from surplus areas to deficit areas through public and private joint efforts.

CONCLUSIONS

(1) Over exhaust of natural resources needs a balanced approach between water resource use and it's regeneration has to reduce natural resource degradation.

(2) Due to an increase in demand for water among different uses per capita availability of water has decreased by 65 per cent during the last about five and a half decade.

(3) In spite of heavy rainfall in the state of Himachal Pradesh, only 20 per cent of the total cropped area has been found to be irrigated, hence productivity of crops has been found to be 2.3 times less than that of irrigated areas.

(4) Government has been giving emphasis on expansion of irrigation through various projects consequently in the state of Himachal Pradesh net irrigated area has increased by about 24.33 per cent during the last decade which has clearly shown shift in cropping pattern, showing growing of more cash crops by farmers.

(5) It has been estimated that only about 6 per cent of the ground water available and about 22 per cent of the surface water available have been found to be utilized for different purposes. Demand for water from these two sources has been found to increase by 3-4 times in future. Hence a scope of exploring possibilities of using water from remaining ground and surface water has been found and need to be exploited through developmental projects on the basis of psycho-scoio-techno-economic parameters.

(6) In the light of scarcity of water, the top priorities of domestic and irrigation show a gap of about 76 per cent. This shows how badly we need management of water' through best planned development projects, however with sustained efforts of multi-disciplinary experts.

(7) Increased demand for water in future which is going to increase still further, hence improper water management may lead to severe consequences in the times to come at micro as well as macro levels.

(8) Micro level parameters like deforestation, soil erosion, floods etc. can be brought to the minimum by proper water management practices which can further lead to balancing of macro level weather parameters like temperature, rainfall, snowfall, humidity etc.

(9). Water harvesting structures have been found to be developed by public sector in collaboration with private sector where heavy investments are involved, whereas roof harvesting by individuals has been found to supplement the water availability to the users.

(10) New methods of irrigation need to be installed in the farms to make better use of water in a cost effective manner leading ultimately to saving of water.

(11) National level awareness programs in the rural/urban areas have been found useful in conserving and utilizing water through universities and development departments in public and private sectors.

(12) The workable location specific and cost effective designs of water harvesting structures in rural as well as urban areas need to be evolved to minimize water scarcity position. For stricter implementation, it has been observed that Government should make such designs mandatory which benefit saving of precious water, avoidance of floods and funds paid for compensating floods.

REFERENCES

Anonymous (1992). Land utilization of H.P. Statistical Outline of H.P. Govt. of H.P. Directorate of Economics and Statistics, Shimla.

Anonymous (2001). Land utilization of H.P. Statistical Outline of H.P. Govt. of H.P. Directorate of Economics and Statistics, Shimla.

Anonymous, (2004). Agrometeorolygical data. Annual Report. Dr. Y.S. Parmar Univ. Hort. & Forestry, Regional Horticultural Research Station, Mashobra, Shimal nil :7.

Anonymous (2005). Agrometeorological Data. Annual Report. Dr. Y.S. Parmar Univ. Hort. & Forestry, Regional Horticultural Research Station, Mashobra, Shimal, H.P. :7.

Anonymous (2005). Economic Review-H.P. Directorate of Economics and Statistics, Shimla: 18

Anonymous (2006). Agrometeorological Data. Annual Report. Dr. Y.S. Parmar Univ. Hort. & Forestry, Regional Horticultural Research Station, Mashobra, Shimal, H.P. :7.

Anonymous 2007. Water Resources. India. (2007). Publication Division. Ministry of Information and Broadcasting, Govt. of India : 851.

Datt Ruddar and K.P.M. Sundharam 2007. Natural Resources, Economic Development and Environmental Degradation. *Indian Economy*. S. Chand and Company Ltd. (An ISO 9001: 2000 company), Ram Nagar, New Delhi-110055 : 99-100.

Randev, A.K. (2005). Impact of Irrigation on productivity and sustainability of Agro-landscapes in Himachal Pradesh, India, 19th Conference at Beijing China, International Commission on Irrigation and Drainage, CD-ROM : 1-13.

Randev, A.K. (2006). Economics of Drip Irrigation System in Himachal Pradesh, India. 7th International Conferrence held at Kaula Lumpur, Malayasia held w.e.f. Sept. 10 to 17. CDROM :1-12.

EFFECTS OF SOCIAL CAPITAL ON PARTICIPATORY MANAGEMENT FOR IRRIGATION FACILITIES: SEM APPROACH

Yoji Kunimtisu[1]

ABSTRACT

Irrigation facilities as common properties have been maintained by mainly farmers, but these are facing difficulties in the maintenance work because of a decrease in population and the aging of farmers. To keep these facilities in good condition with help from local communities, social capital (SC) needs to play an important role in Japan. This paper aimed to empirically analyze causative factors and effects of SC with consideration of geographical conditions. A structural equation model with latent variables (SEM/LV) was estimated from the data based on statistics and questionnaire survey in Shizuoka prefecture, Japan. The results indicated that the effect of SC was positive in participation in maintenance of irrigation facilities by non farmers as well as an improvement of satisfaction index. These effects were higher in the hilly and mountainous areas than urban and suburban areas. Therefore, improving SC is critical for preserving common properties and maintaining high satisfaction of residents which compensates for relatively low income especially in the less favored area where economic development is difficult but necessary. By using SEM/LV, such relations on SC can be empirically measured by the data, showing validity of this model.

INTRODUCTION

Irrigation facilities are one of the critical common properties for agricultural production as well as preservation of natural environment. However, some of these facilities maintained by farmers are facing difficulties in the maintenance work because of a decrease in population and the aging of farmers. Even the land improvement district, which is the irrigation water users' group for maintenance of irrigation facilities in Japan, is decreasing strength of bonding among members. To keep these facilities in good condition, help from local communities is highly needed in many areas. Previous case studies (Ostrom, 1995; Isham and Kahkonen, 1999) pointed out that the social capital (SC) improves altruistic activities of residents and helps non-farmers act cooperatively as participatory management for irrigation facilities. Considering this role of SC, Japanese agricultural policy started to support participatory management of communities for common properties by subsidizing several activities of residents.

The concept of SC, mostly defined by trust, cooperative norms and associations within groups, has been mentioned by scholars since the 1970's (Coleman, 1990). After Putnam’s work (1993) on South Italy, SC was highlighted in the field of social science. He focused on relations of residents embedded in the social structure among above features of SC, and pointed out that SC could improve the performance of administrative works. Recently several studies have been conducted to show its effects on income (Narayan and Pritchett, 1996; Burt, 1997), effects in

[1]Chief Researcher - Project Evaluation; National Institute for Rural Engineering (NIRE); 2-1-6, Kannondai, Tsukuba, Ibaraki, 305-8609, Japan; ykuni@affrc.go.jp

collective action at the community level (Molinas, 1998) and negative impact on corruption in political and government institutions (Evans, 1996).

Regarding Japan, several case studies have been conducted on activities in rural communities, and several questionnaire researches have tried to depict causative factors of participants in activities (Ando, 2002). However, there were few empirical analyses on effects and causative factors of SC. In order to prove the effects of SC, economic model statistically estimated by concrete data is needed in view of policy decision on preservation of common properties as well as subsidies to activities in the local community as mentioned above.

This paper aimed to empirically analyze causative factors and effects of SC in participatory management for irrigation facilities. A structural equation model with latent variables (SEM/LV) was estimated from the data based on statistics and questionnaire survey in Shizuoka prefecture, Japan. Since SC is general idea and cannot be measured by the direct way, the SEM/LV is useful to depict SC as a latent variable and build the causal relation model (Narayan and Cassidy, 2001).

After this section, section two explains the model and the working hypothesis about SC, and introduces the data used in detail. Section three discusses estimation results of the model with consideration of geographical situations, and final section provides the summary and conclusion for policy implications.

METHOD

<u>Structural Equation Model with Latent Variables (SEM/LV)</u>

SEM/LV is increasingly used for modeling the complicated situation, especially in the fields of psychology and sociology. This method is a combination of the factor analysis and the pass analysis using the regression analysis. One of the merits of this method is to introduce the latent variable, which is hardly measured by statistics, into the model in revealed form together with the observable variables. Even in the field of economics, there are some previous studies, which used this method (Kunimitsu, 2004 and Sasaki, 2005).

In general, the SEM/LV can be defined as;

$$\begin{aligned} \mathbf{f} &= \mathbf{A_a f} + \mathbf{A_d v} + \mathbf{d}, \\ \mathbf{v} &= \mathbf{A_b f} + \mathbf{A_c v} + \mathbf{e} \end{aligned} \qquad (1)$$

Here, **f** shows latent variables which exist beneath the observable situations, and **v** shows observable variables for which researchers can measure as data. The bold characters denote vector or matrix, afterwards. The size of vector is ($n_f \times 1$) for **f** and ($n_v \times 1$) for **v**, and n shows the number of concerned variables. The $\mathbf{A}_a$, $\mathbf{A}_b$, $\mathbf{A}_c$ and $\mathbf{A}_d$ are coefficient matrixes and their sizes are ($n_f \times n_f$), ($n_v \times n_f$), ($n_v \times n_v$) and ($n_f \times n_v$), respectively. The ‘d’ and ‘e’ are error term.

To estimate coefficients shown by **A**, Eq. (1) is described as $\mathbf{t} = \mathbf{At} + \mathbf{u}$ and $\mathbf{v} = \mathbf{Gt}$.

Here, $\mathbf{t} = \begin{bmatrix} \mathbf{f} \\ \mathbf{v} \end{bmatrix}$, $\mathbf{A} = \begin{bmatrix} \mathbf{A}_a & \mathbf{A}_d \\ \mathbf{A}_b & \mathbf{A}_c \end{bmatrix}$, $\mathbf{u} = \begin{bmatrix} \mathbf{d} \\ \mathbf{e} \end{bmatrix}$, $\mathbf{G} = [\mathbf{0} \quad \mathbf{I}]$ and I is the unit matrix. Supposing that the inverse matrix of (**I**-**A**) exists, structural variable vector **t** and observable variable vector **v** can be defined as;

$$\mathbf{t} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{u} = \mathbf{Tu}, \quad \mathbf{v} = \mathbf{GTu} \tag{2}$$

From Eq. (2), variance of observable variables can be defined as;

$$\mathbf{\Sigma} = E[\mathbf{vv}'] = \mathbf{GT}E[\mathbf{uu}']\mathbf{T}'\mathbf{G}' \tag{3}$$

When the sample variance covariance matrix is denoted by **S** and parameters which defines Σ obey multivariate normal distribution, the objective function to be minimized can be defined as (Toyoda, 1998);

$$f_{ML} = tr(\mathbf{\Sigma}^{-1}\mathbf{S}) - \log|\mathbf{\Sigma}^{-1}\mathbf{S}| \tag{4}$$

Estimations of **A** can be obtained by minimizing f_{ML} with fitting parameters of Σ to normal distribution with using maximum likelihood method.

Figure 1 shows the working hypothesis on causative factors on SC in this study. Considering novel studies of Putnam (1993), the SC is probably revealed in activities of residents, such as participation in events, altruistic action like flower planting on the road, participatory planning for a public projects, and the number of female entrepreneur (arrow A). In the same way, SC is represented by revitalization level (arrow B). If the level of SC is high in the community, such activities would gain force.

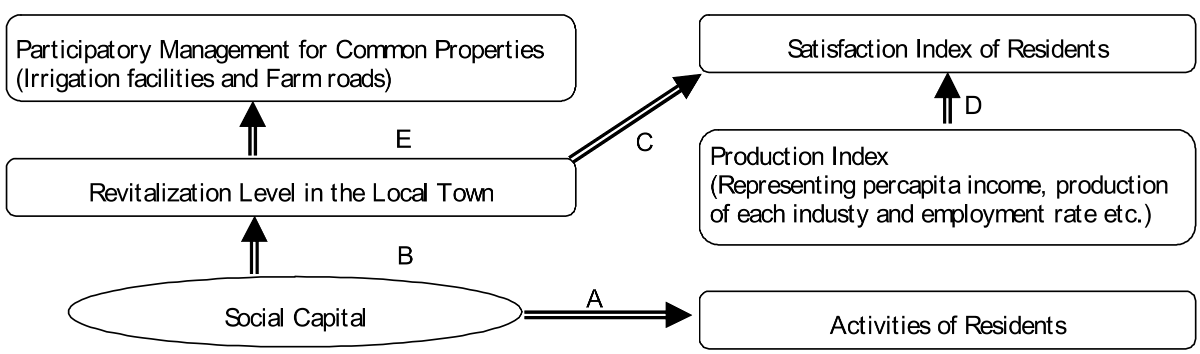


Figure 1. Causative Factors on Social Capital and Preservation of Irrigation Facilities

Second, if revitalization index of community is high in accordance with the high level of SC, the satisfaction index of residents would be improved (arrow C). This is because residents can feel comfort with good human relations. Satisfaction index would also be improved by economic situation based on the production index (arrow D).

Third, high level of revitalization activities would bring about good results for participatory management of the common property, such as irrigation facilities and roads in the region (arrow E). Participatory management would mainly consist of operation and maintenance for these facilities with help from not only farmers but also non-farmers in the local town[2].

Data

The data based on town were used as the unit area for the analysis. This is because the minimum unit of administration is a town in Japan. Each town decides own policies by the mayor and members of town assembly, so the target of policy decision would be focused on the town unit. Also, the minimum unit of social economic data is town in Japan, and there is few data on community level which is smaller in size than town.

On average of 71 towns in Shizuoka prefecture in 2000, total area of one town is 116 km^2 and inhabitable area, consisting of residential area, agricultural area and public space, accounts for about 30% of the total area in a town. Considering distance of about 20 minutes by car to neighboring town, a town is the life circle of residents' everyday life. The population in a town is about 43000 on the average.

Table 1 shows the variables used for the SEM/LV. The variables which cannot exist in the official statistics were estimated as follows.

Satisfaction index was investigated in each town by the questionnaire to residents. Following to the method of *World Values Survey* (http://www.worldvaluessurvey.org/), the residents in each town were asked question as "How much degree are you satisfied with your town? Could you select the suitable degree among following degrees from 10 for very satisfied to 1 for very unsatisfied with 5 for average, or either cannot be said?" From the scores marked by each resident, the average points of town were calculated as the satisfaction index, so the satisfaction index, in other words, indicates the rate of people who replied to the question with high satisfaction.

Revitalization level of the community and other activity levels were measured by questionnaire of staff members who are in charge of rural development in the municipality. This questionnaire was conducted in 2004. Five members in each municipality were randomly designated and asked to mark the revitalization level of their town on a scale of 1 to 100 from their own view. This measurement method was proposed in the research of Takemoto (2001). The score marked by examinees was the self-evaluation value about residents' activity. However, their score is rather comprehensive, because they can get a general view of residents' activities and can obtain information about residents' request and complaint. There may be variances of their points, but such variance is assumed to be offset by several samples. Hence, the town where many

[2] Main canals, pumping stations and headworks are operated and maintained by LDCs and small facilities belong to each farmer. Since some facilities like canals relate to the residents' life base and local environment, these have been cleaned and repaired by cooperation of residents for long time. Under decreasing trend in bonds of the local communities, SC can reinforce such cooperation for the maintenance of irrigation facilities by improving participation of non-farmers as well as farmers.

examinees mark high score could be higher in score of activity index. The staff members may have overestimated their own town. Even so, the town of which they are proud of with strong confidence would be the good town in terms of revitalization level, because they play an important role in town[3].

In addition, staff members were asked to rate other activities, such as participatory planning to public projects, participation in events and festivals, altruistic action in flower planting on the road, and degree of female entrepreneur activities.

Table 1. Variables of SEM/LV

Variables	Unit	Contents	Source
v1	1 to 10	Satisfaction Index	Questionnaire to residents
v2	0 to 100	Revitalization Index	Questionnaire to officers in charge
v3	rate	Operation and Maintenence for canals	Agricultural Census 2000
v4	rate	Operation and Maintenence for roads	Agricultural Census 2000
v5		Production Index	composited from statistics (percapita income etc.) shown in Table 2
v6	-2 to 2	Participatory Planning	Questionnaire to officers in charge
v7	-2 to 2	Participation in festivals and events	Questionnaire to officers in charge
v8	-2 to 2	Participation in activities for beatification and environment preservation	Questionnaire to officers in charge
v9	-2 to 2	Femail Enterpreneurship	Questionnaire to officers in charge
f1		Social Capital	latent variable

Table 2. Contents of Production Index

Variables	Contents	Sources
Static situations		
Per capita income	taxable income/ population	Japan Market Research Center
Employment absorption rate	num. of workers/ population 16-65 *100	Firm Statistics
Per capita industry production	Industry production/ total population	Industastry Statistics
Per capita commerce production	Sales of commerce/ total population	Commerce Statisitics
Rate of employees in 3rd industry	employees in 3rd ind./ total population *100	National Census
Financial power index of town		
Dynamic situations		
Change in taxable income	taxable income (2000 / 95): %	Japan Market Research Center
Change in firm employees	Firm employees (2000 / 95): %	Firm Statistics
Change in industry production	Industry production (2000 / 95): %	Industastry Statistics
Change in commerece production	Commerce production (2000 / 95): %	Commerce Statisitics
Change in employees in 3rd ind.	Employees in 3rd industry (2000 / 95): %	National Census

Production index was composed by the scores of the principal component abstracted from statistics in Table 2 (Hashizume, 2004). Most data were per capita value divided by population in order to control difference in town size. The static and dynamic variables were calculated from the first principal component scores in the Principal Component Analysis. Then, values of the

[3] We conducted similar questionnaire survey in other prefectures, Niigata (2004), Yamagata (2005) and Yamaguchi (2006), and found almost the same effects as this study. There may be some rooms to be improved in the questions, but this method can represent revitalization level of rural towns.

static and dynamic variables were added up assuming that they can be evaluated at the same weight. The contribution ratios of the first principal component were 39.9 % and 57.0 % (static and dynamic groups of data).

RESULTS

Estimations of SEM

Based on the working hypothesis shown in Fig. 1, the SEM/LV was estimated by the maximum likelihood method used generally in the previous studies. The AIMOS (ver. 5 by SPSS inc.) was used for estimation, and results were validated by the MPlus (ver. 3 by Muthen and Muthen inc.). The result in Fig. 2 shows the pass coefficients with all variables standardized as 0 mean and 1 standard deviation. Table 3 shows the non-standardized coefficients calculated by the original values of variables without standardization.

The performance of this model was relatively good as seen by the goodness-of- fit-index (GFI) and the root-mean-square-error-of-approximation (RMSEA) as compared to the standard values which are said to be over 0.9 for GFI and less 0.05 for RMSEA (Browne and Cudeck, 1993; Hu and Bentler, 1999). RMSEA is worse than the standard value, because of low correlation coefficients between variables disturbed by other intangible factors. However, this value can be within the allowable range for latter analysis. Also $\chi 2$ value is low and p-value for this statistics is more than 0.1, showing that the null hypothesis of rightness of the model structure cannot be rejected and this model is statistically significant. Notice that rejection of null hypothesis in SEM/LV means insignificant structure of the model estimated, in reverse to the common statistical testing.

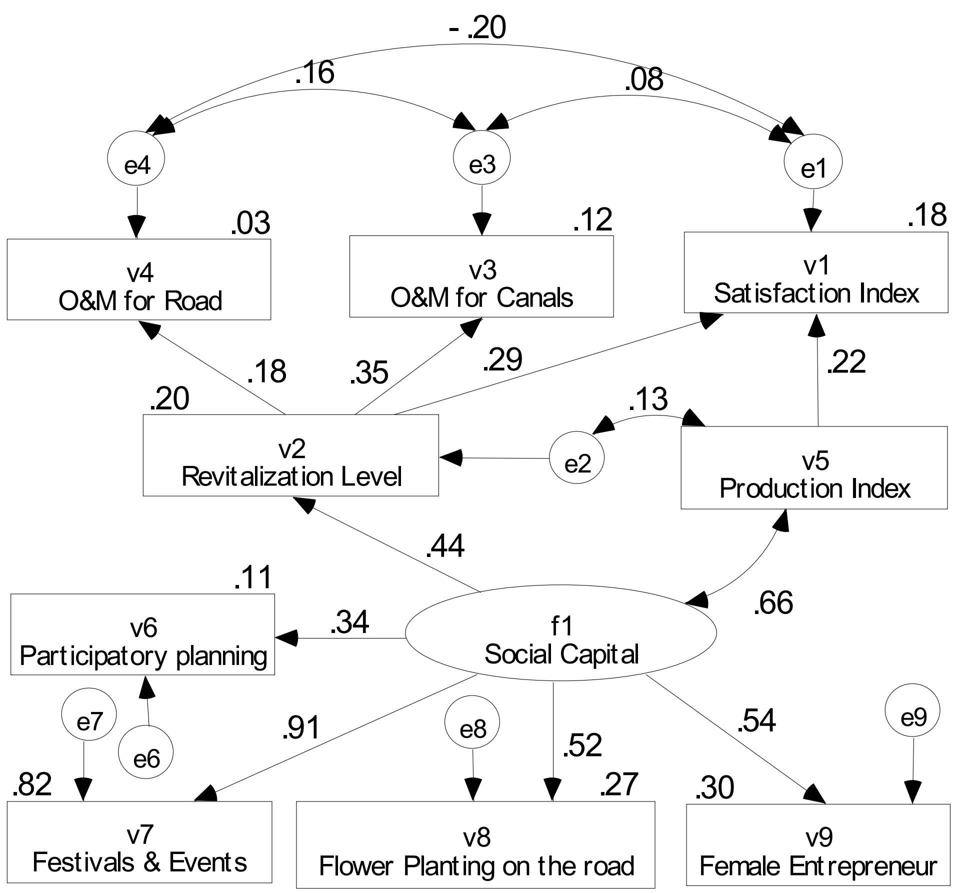
All coefficients estimated from the data are consistent to the working hypothesis explained in former section, and most of them are statistically significant as compared to t-statistics in 5 % significance level. It can be said that the model estimated here describes major relations between SC and economic variables well.

Five activity levels, such as the revitalization level, participatory planning, participation in events and festivals, altruistic action of flower planting, and female entrepreneur, were correlated each other, so the level of SC was measured by these variables. Among them, the level of SC was represented by the participation in events and festivals rather than other activities. This tendency corresponds to previous study (Narayan, 1996) in which SC was represented by the number of participants in the events. From these pass coefficients, it can be possible to see that there is a construct, which is a latent factor and is called as SC in this study, under residents' activities and towns where SC is in high level can achieve revitalization.

In terms of effects of revitalization level, 10% increase in this level can improve the level of management for irrigation facilities by 3.5%. 10 % increase in this level can also improve management level of roads by 1.8%, even though the pass coefficient of this part was statistically insignificant.

The pass coefficient of satisfaction index from revitalization level was 0.29, showing remarkable positive influence in this part. Satisfaction index can also be improved by the production index, but this effect (0.22) was lower than that of revitalization level. These effects indicate that people, who obtain high income and stable job opportunity, are more satisfied with their life than others, and people, who live in the town revitalized by SC, are also satisfied with good relations to neighbors. This corresponds to the socio-economic theory and our intuition.

From above estimation results, it can be said that improving SC is critical for preserving common properties and maintaining local communities with high satisfaction of residents especially in rural areas.



Note: GFI=0.901, RMSEA=0.065, $\chi 2$=27.19 (df=22) (p-value=0.204)

Figure 2. Estimations of SEM/LV (Standardized Solution)

Table 3. Estimations of SEM/LV (Non Standardized Solution)

Para-meters	Dependent and independent variables			Estimates	t-stat.	p-val.
a12	v1	<--	v2	0.016	2.2	0.03
a15	v1	<--	v5	0.067	1.7	0.09
a2	v2	<--	f1	18.246	3.0	0.00
a32	v3	<--	v2	0.005	2.8	0.01
a42	v4	<--	v2	0.005	1.3	0.18
a6	v6	<--	f1	0.468	2.3	0.02
a7	v7	<--	f1	1		
a8	v8	<--	f1	0.391	3.6	0.00
a9	v9	<--	f1	0.442	3.8	0.00

Estimations of SEM/LV by Geographical Situations

Table 4 shows the standardized coefficients in each region classified by geographical situations. They were estimated by data classified into two groups, such as urban-and-suburban towns (33 towns) and hilly-and-mountainous towns (23 towns).

Statistical performance of the model estimated was not good in the urban-and-suburban case as compared to other cases. There may be some other factors which affect to the satisfaction index in this area. However, performance of the model in hilly and mountainous towns was high, showing highly significant relations among factors.

Table 4. Standardized Pass Coefficients by Geographical Situations

Para-meters	Dependent and independent variables			All towns	Urban and Suburban towns	Hilly & Mountainous towns
a12	v1	<--	v2	0.289	0.274	0.279
a15	v1	<--	v5	0.220	0.000	0.372
a2	v2	<--	f1	0.444	0.348	0.414
a32	v3	<--	v2	0.350	0.051	0.630
a42	v4	<--	v2	0.177	0.206	0.226
a6	v6	<--	f1	0.336	0.190	0.370
a7	v7	<--	f1	0.907	0.783	0.910
a8	v8	<--	f1	0.520	0.550	0.695
a9	v9	<--	f1	0.544	0.597	0.560
	GFI			0.90	0.83	0.87
	RMSEA			0.065	0.115	0.000
	χ^2			27.2	32.7	15.7
	(p-value)			0.20	0.09	0.83

Estimations of the coefficients a15 and a42, which show relations of production index to satisfaction index and revitalization index to management level for irrigation facilities, respectively, were both insignificant in the urban and suburban towns. However, these coefficients in the hilly and mountainous towns were significant and higher than the all town case, showing economical and social activity level is important in these areas. Generally, economic development is difficult in the hilly and mountainous areas, but instead, SC can contribute to keep high satisfaction level of residents, attracting residents to the local community.

Effects of SC

Table 5 shows the comprehensive effects of SC on each factor. These values were calculated by the multiplied pass coefficients concerned according to the pass arrows in the normalized solution.

First, the effects of SC on satisfaction index were high and almost the same in the all town case and the hilly and mountainous town case, but this effect was lower in the urban and suburban town case. In the hilly and mountainous towns, migration of people is rare and society is relatively fixed, so human relations and networks supported by SC are quite important in the daily life. In this sense, SC plays more important role in these less favored areas.

Second, in terms of protection for common properties, the SC marked the highest effect in participatory management of irrigation facilities supported by not only farmers but also non-farmers. This effect was especially high in hilly and mountainous towns. Although the effect in farm roads was lower than irrigation facilities, positive effect of SC was seen in this table. Therefore, effects of SC are revealed in preservation of local common properties like irrigation facilities.

Table 5. Comprehensive Effects of SC

Target variables	All towns	Urban and Suburban towns	Hilly & Mountainous towns
Satisfaction Index	0.128	0.097	0.116
O&M for canals	0.155	0.018	0.261
O&M for roads	0.079	0.072	0.094

SUMMARY AND CONCLUSION

This paper aimed to analyze causative factors and effects of social capital, which can be seen as residents' active interaction in the rural community, in view of performance in satisfaction level of residents and participatory management for irrigation facilities. A structural equation model was estimated from the data based on statistics and questionnaire to residents.

The results suggest that the model can describe causal relations of economic and social factors with statistically high significant level. The model, also, makes it clear that the SC can be revealed by residents' activities in the community. This indicates that residents' activity level is the good proxy for the level of SC, as pointed out by previous studies. Then, the high level of SC results in high satisfaction level of residents via revitalization of local communities. On the other hand, the SC improves participatory management of irrigation facilities by not only farmers but also non-farmers. These effects are especially high in the hilly and mountainous areas, showing important role of SC in these areas. In this sense, it is important to keep the satisfaction level high by stimulating SC with agricultural policy which tries to improve participatory management of irrigation facilities. This is also thought to bring about sustainable development of local communities.

Above results were usually pointed out by researchers in qualitative way, but were rarely evaluated by the real data. By using SEM/LV, such relations on SC can be empirically shown with statistical testing, showing usefulness of SEM/LV in policy evaluation.

Of course, there are some issues remained. An application of this model to other regions may be useful to generalize and evaluate SC. An improvement of measurement method for the level of several indexes used is highly needed, because these indexes were key data for this model. Finally, although this study used aggregate data by the town, the data on attributes of individual resident should be taken into consideration. By using individual data, more vivid effect can be found in this field.

APPENDIX

The concrete equation of the model shown by Eq. (1) and Fig. 2 is;

$$\begin{aligned}
&f_1 = f_1 \quad , v_1 = a_{1\cdot 2} v_2 + a_{1\cdot 5} v_5 + e_1 \, , \\
&v_2 = a_2 f_1 + e_2 \quad , v_3 = a_{3\cdot 2} v_2 + e_3 \, , \\
&v_4 = a_{4\cdot 2} v_2 + e_4 \quad , v_5 = v_5 \, , \\
&v_6 = a_6 f_1 + e_6 \quad , v_7 = a_7 f_1 + e_7 , \quad a_7 = 1 \, , \\
&v_8 = a_8 f_1 + e_8 \quad , v_9 = a_9 f_1 + e_9
\end{aligned} \tag{5}$$

Here, v_5 is a exogenous variable and has $a_5 = 1, e_5 = 0$. The equations of $a_7 = 1$ is a restriction to fix the variance of the latent variables on one.

REFERENCES

Ando, M (2002) "The regional variety of the agricultural commune and its adjustment function for area resources control and land use (in Japanese)," Shogenji, S. ed. *The fundamental structure of Japanese agriculture in the 21st century*, Norin Tokei Kyokai, pp.170-239.

Browne, M. W. and Cudeck, R. (1993) "Alternative ways of assessing model fit," Bollen, K. and Long, J.S. eds., *Testing Structural Equation Models*, SAGE Publications, pp.137 - 162.

Burt, R.S. (1997) "The contingent value of social capital," *Administrative Science Quarterly*, 42(2), pp.339-365.

Coleman, J.S. (1990) *Foundations of Social Theory*, Cambridge, MA, Harvard Univ. Press.

Evans, P. (1996) “Government action, social capital and development: Reviewing the evidence on synergy,” *World Development*, 24(6), pp.1119-1132.

Hashizume, N. (2003) “The activated conditions and vitality diagnosis on the rural areas: Comparison by the vitalization index between towns in Japan (in Japanese),” *The research materials of the project on village economic vitalization*, Policy Research Institute of Ministry of Agriculture, Forestry and Fishery, 4, http://www.primaff.affrc.go.jp/seika/ kankou/project/ nosonkeizai/nosonkeizai4.html.

Hu, L. and Bentler, P. M. (1999) “Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives,” *Structural Equation Modeling*, 61, pp.1 - 55.

Isham, J. and Kahkonen, S. (1999) “What Determines the Effectiveness of Community-based Water Projects ?: Evidence from Central Java, Indonesia on Demand Responsiveness, Service Rules, and Social Capital,” *Social Capital*, Initiative Working Paper, 14, Washington, D.C.; The World Bank.

Kunimitsu, Y., (2004) “Effects of social infrastructure in rural economies: Application of the covariance structure model (in Japanese),” *Transactions of Agricultural Economics Society of Japan*, pp.263 - 270 .

Molinas, J.R., (1998) “The impact of inequality, gender, external assistance and social capital on local-level cooperation,” World Development, 26(3), pp.413-431.

Narayan, D. and Pritchett, L. (1996) “Cents and Sociability: Household Income and Social Capital in Rural Tanzania,” *Policy Research Working Paper*, 796, Washington, D.C., The World Bank.

Narayan, D. and Cassidy, M.F. (2001) “A Dimensional Approach to Measuring Social Capital: Development and Validation of a Social Capital Inventory,” *Current Sociology*, SAEGA Publications, pp.59-102.

Ostrom, E. (1995) “Constituting Social Capital and Collective Action,” Keohane R. et al. eds, *Local Commons and Global Interdependence: Heterogeneity and Cooperation in Two Domains*, London; SAGE.

Putnam,R.(1993) ”Making Democracy Work: Civic Traditions in Modern Italy,” *Princeton University Press*, New Jersey.

Sasaki, H. (2005) “Analysis about Consciousness Structures on Agri-Environmental Payment

Programs in Shiga: An Application of Structural Equation Model included WTP (in Japanese)," *Journal of Rural Planning Association*, 23(4), pp.275 - 284.

Takemoto, T. (2001) "A trend of "beautiful and comfortable areas to live in and the new direction of regional development to see for the questionnaire (in Japanese)," *Report of RDPC,* pp.42-81.

Toyoda, T. (1998) "Structural Equation Model (in Japanese)," Toyoda ed. *Covariance Structure Analysis –Initiation Edition*-, Asakura Shoten, Tokyo, pp.88 - 108.

BEET FIELDS TO BALL FIELDS — ADAPTATION OF THE COLORADO-BIG THOMPSON PROJECT TO CHANGING WATER NEEDS

Gerald Gibbens, P.E.[1]
Andy Pineda, P.E.[2]

ABSTRACT

The Colorado-Big Thompson Project (C-BT) delivers approximately 213,000 acre-feet of water annually to Northern Colorado. Water is diverted from the Colorado River Basin to the South Platte Basin through a system of 12 reservoirs with a total storage capacity of nearly 1 million acre-feet, 35 miles of tunnels, 95 miles of canals, three pumping plants and six hydroelectric power plants with an installed capacity of 216 megawatts. The Northern Colorado Water Conservancy District (District) was created in 1937 to contract with the U.S. Bureau of Reclamation (Reclamation) for construction and repayment of project facilities and jointly operates and maintains C-BT with Reclamation. The District is responsible for allocation, administration and delivery of C-BT water to allottees.

C-BT initially provided supplemental water to approximately 720,000 irrigated acres within District boundaries. However, as the population within the District has grown from 200,000 in 1950 to 750,000 today, C-BT has transitioned to a system that provides both agricultural and municipal supplemental water needs. The allocation system employed by the District to distribute the water provides a reliable, consistent and flexible method to transfer water between water users within the District. Short-term rentals and long-term purchases and transfers of water allotment contracts are performed as free-market transactions, so long as the transfer occurs within District boundaries, meets District requirements and is approved by the District's Board of Directors. In addition, the District has implemented numerous rules and programs that provide additional flexibility and maximize benefits to all District constituents, including the Annual Carryover Program, the Carryover Capacity Transferability Program, and the Regional Pool Program. These programs allow allottees to manage their annual allocations for year-round water demands while promoting temporary leases of municipal water to agricultural users. The administration of these programs, along with the transitional nature of C-BT operations and deliveries from agricultural to municipal uses, presents unique challenges to Reclamation and the District as they attempt to maximize benefits of the resource.

INTRODUCTION AND BACKGROUND

The District is a public agency created in 1937 under Colorado's Water Conservancy Act (Colorado Revised Statutes § 37-45-101 et seq.). Its original purpose was to contract with Reclamation to build C-BT. The federally owned project is jointly operated and maintained by the District and Reclamation. C-BT provides supplemental water for agricultural, municipal,

[1] Senior Water Resources Engineer; Northern Colorado Water Conservancy District; 220 Water Avenue, Berthoud CO 80513, (970) 622-2299, (970) 532-2517; jgibbens@ncwcd.org
[2] Supervisory Water Resources Engineer; Northern Colorado Water Conservancy District; 220 Water Avenue, Berthoud CO 80513, (970) 622-2330, (970) 532-2517; apineda@ncwcd.org

domestic and industrial uses in northeastern Colorado. An estimated 750,000 people live in the District. Its boundaries encompass nearly 1.5 million acres in portions of Boulder, Broomfield, Larimer, Logan, Morgan, Sedgwick, Washington and Weld counties. The total value of agricultural production within District boundaries is more than $300 million annually. Water assessments and ad valorem taxes form the District's primary revenue base. A map showing C-BT and the District boundaries is presented in Figure 1.

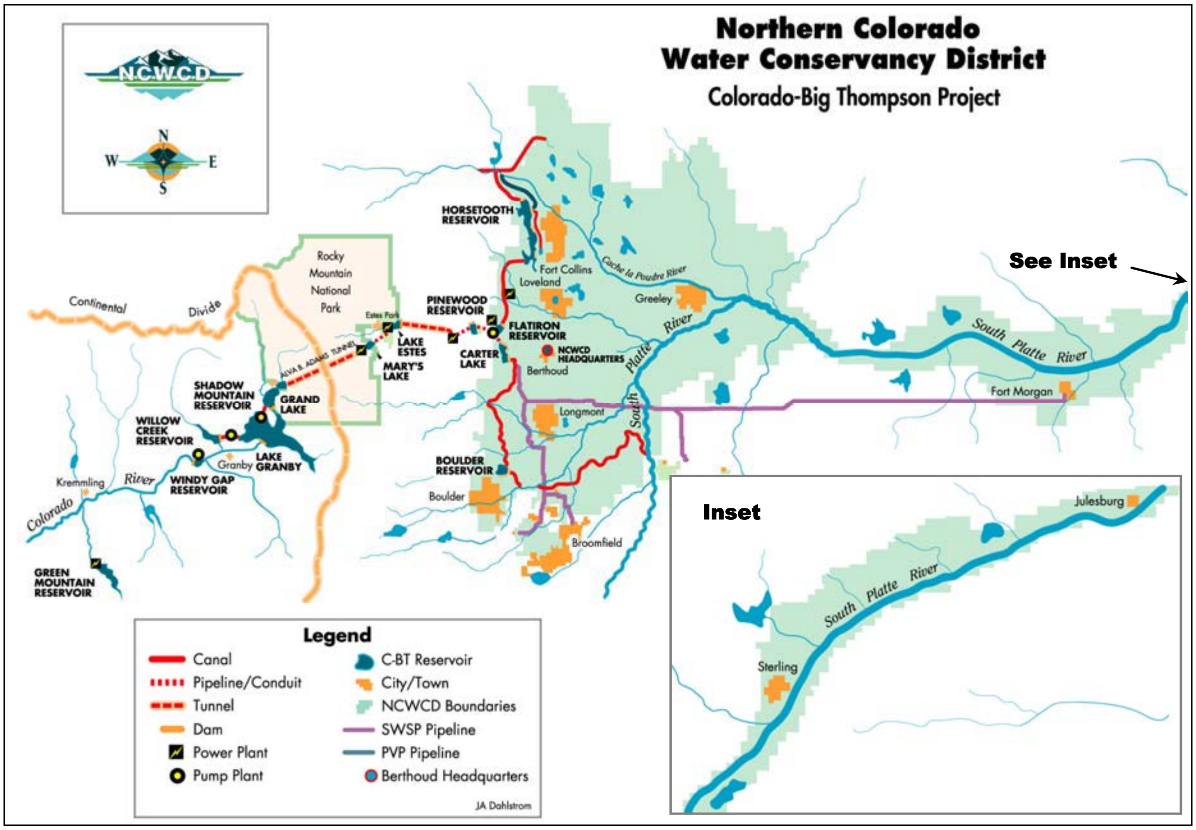


Figure 1. Location Map C-BT and District

Description of the Colorado-Big Thompson Project

C-BT is Colorado's largest transmountain diversion project. The project was authorized as a federal reclamation project by Congress on June 24, 1937 with the approval of Senate Document 80 (Reclamation, 1937). The project was built from 1938 to 1957 with a final construction cost of $164 million, and provides supplemental water to 32 cities and towns and more than 100 ditch and reservoir companies. C-BT water currently irrigates approximately 690,000 acres of farmland. The complex collection, distribution and power system consists of 12 reservoirs, 35 miles of tunnels, 95 miles of canals and 700 miles of transmission lines. It spans 150 miles east to west and 65 miles from north to south. The system is designed to collect and deliver up to 310,000 acre-feet of water annually from the Upper Colorado River Basin. It transports this water via a 13.1-mile tunnel beneath the Continental Divide to the Front Range. A summary of storage capacity for C-BT reservoirs is presented in Table 1.

Table 1. C-BT Reservoir Storage Capacities

	Dead Storage (1) (acre-feet)	Active Storage (2) (acre-feet)	Total Storage (acre-feet)
West Slope Replacement Storage			
Green Mountain	6,860	146,779	153,639
West Slope Collection System			
Willow Creek	1,486	9,067	10,553
Lake Granby	74,190	465,568	539,758
Shadow Mountain	506	16,848	17,354
Grand Lake	(3)	1,015	1,015
Sub-Total	76,182	492,498	568,680
East Slope Distribution System			
Marys Lake	42	885	927
Lake Estes	409	2,659	3,068
Pinewood Lake	416	1,765	2,181
Flatiron	125	635	760
Carter Lake	3,306	108,924	112,230
Horsetooth	7,003	149,732	156,735
Sub-Total	11,301	264,600	275,901
Total	94,343	903,877	998,220
Total without Green Mountain (4)	87,483	757,098	844,581

Notes:
(1) Storage capacity below elevation of lowest outlet
(2) Total storage minus dead storage
(3) Not determined
(4) Water stored in Green Mountain Reservoir cannot be diverted through the Adams Tunnel. It is used for downstream West Slope water and power obligations.

<u>West Slope Collection System</u> C-BT's West Slope facilities consist of four reservoirs and two pumping plants. The system collects high mountain runoff for diversion to the East Slope. Most of this water is stored in Lake Granby, accumulating mainly during spring snowmelt. Water is also collected in Willow Creek Reservoir and pumped to Lake Granby via the Willow Creek Pumping Plant and Willow Creek Canal. From Lake Granby, water is pumped to the Granby Pump Canal via the Farr Pumping Plant where it flows into Shadow Mountain Reservoir and through a connecting channel to Grand Lake. On Grand Lake's southeast shore, water enters the Alva B. Adams Tunnel on its way to the East Slope.

Green Mountain Reservoir stores Blue River water to meet downstream water and power obligations on the Colorado River. Following project construction, irrigation systems below C-BT facilities were enhanced to ensure continued use of existing Colorado River water rights. In 1961 the District agreed to provide minimum streamflows below Lake Granby, the first such flows ever established below a Reclamation facility.

Alva B. Adams Tunnel The 13.1-mile Adams Tunnel, lynchpin of C-BT, is the nation's longest water tunnel built for irrigation. Constructed between 1940 and 1947, the tunnel drops 108 vertical feet from west to east, enabling gravity to carry water beneath the Continental Divide to the East Slope in less than three hours. The tunnel's capacity is 550 cubic feet per second (cfs). The Adams Tunnel is named for a Colorado senator who championed C-BT in Congress. Reclamation regularly inspects the tunnel.

East Slope Distribution System C-BT's East Slope Distribution System facilitates water storage and delivery throughout the District. After water exits the Adams Tunnel's east portal, it is used to generate electricity, dropping almost a half mile through five power plants to the Front Range. Water is stored in three terminal Front Range reservoirs: Horsetooth Reservoir, Carter Lake and Boulder Reservoir. Horsetooth Reservoir primarily serves the District's northern region while Carter Lake and Boulder Reservoir supply the District's southern area. These facilities are also able to capture and store water for use by the District when the decreed East Slope water rights for these facilities are in priority under Colorado water law.

The District releases water to farmers, industries and municipalities upon request subject to the amount of water available in their accounts. Agricultural water deliveries occur between April and October, the primary growing season. Municipal and industrial users may request water during the same period or take year-round deliveries directly from project reservoirs, the Southern Water Supply Project Pipeline, or the Pleasant Valley Pipeline. C-BT provides a reliable, supplemental water supply to Fort Collins, Greeley, Loveland, Longmont, Boulder, Louisville, Lafayette, Broomfield, many smaller communities, numerous rural domestic water districts, and industrial users such as Kodak, IBM and Hewlett Packard.

Allocation and Allotment Contracts

Under the District's contract with the United States for repayment of C-BT (Repayment Contract; United States, 1938), the District has the perpetual rights to use all water that becomes available through the construction and operation of the project. The uses of this water may be for irrigation, domestic, municipal and industrial purposes. Based on this authority, it is the District's responsibility to determine the method and to allocate all C-BT water.

An allotment contract is the method the District uses to allocate the water supplies collected by C-BT. The District issued 310,000 allotment contracts and refers to entities that own allotment contracts as allottees. Water users are required to petition to the District's Board of Directors for an allotment of water. The allotment contracts are grouped into three classifications: (1) class B for municipalities, (2) class C for corporations (irrigation or domestic use), and (3) class D for irrigation of specific tracts of land. In 1957 approximately 85 percent of the allotment contracts were class D and class C (irrigation) contracts.

Language in every contract specifies that one acre-foot of water is one-three-hundred-ten-thousandth (1/310,000) of the quantity of water annually declared available by the Board of Directors. Thus, the volume of water described on the contract became known as the number of acre-foot units, or AFUs. Allotment contracts may be transferred in whole or part to different users. This provides the basis for short-term and long-term rentals and leases of C-BT water as well as permanent transfers of allotment contracts between District entities.

The Water Conservancy Act states the Board is responsible for allocating the water but does not specify a particular water allocation method. Likewise, there is no reference to a quota-setting process in Senate Document 80 (SD80; Reclamation, 1938). SD80 defines the overall operation and the supplemental nature of C-BT but does not constrain the Board as to the methodology to use. In March 1963, a special Board meeting was held where Director W.D. "Bill" Farr gave a presentation explaining the quota-setting process (District, 1963). Mr. Farr explained that initial planning projections of the amount of supplemental water C-BT needed to provide for the region to have a full water supply averaged 310,000 acre-feet per year. However, it was clear by this time that the firm yield of C-BT was going to be less than this number. Thus, the Board needed a process to allocate the available supply in light of the less than ideal amount of anticipated inflows. In his presentation Farr states: "It is our view and hence our policy to make the annual quantity of water which is produced, available at the times and in the amounts which will most nearly equalize or level out the total supply of all the water available for use throughout the service area. In the simplest terms, this means that we would release the highest quota in the years when local storage and local runoff are low and the supplemental needs are the greatest." This same methodology is still used today. A summary of annual quotas (the percentage of a full water supply made available each year) and resulting allocations (the volume of water supply made available by the quota) is presented in Figure 2.

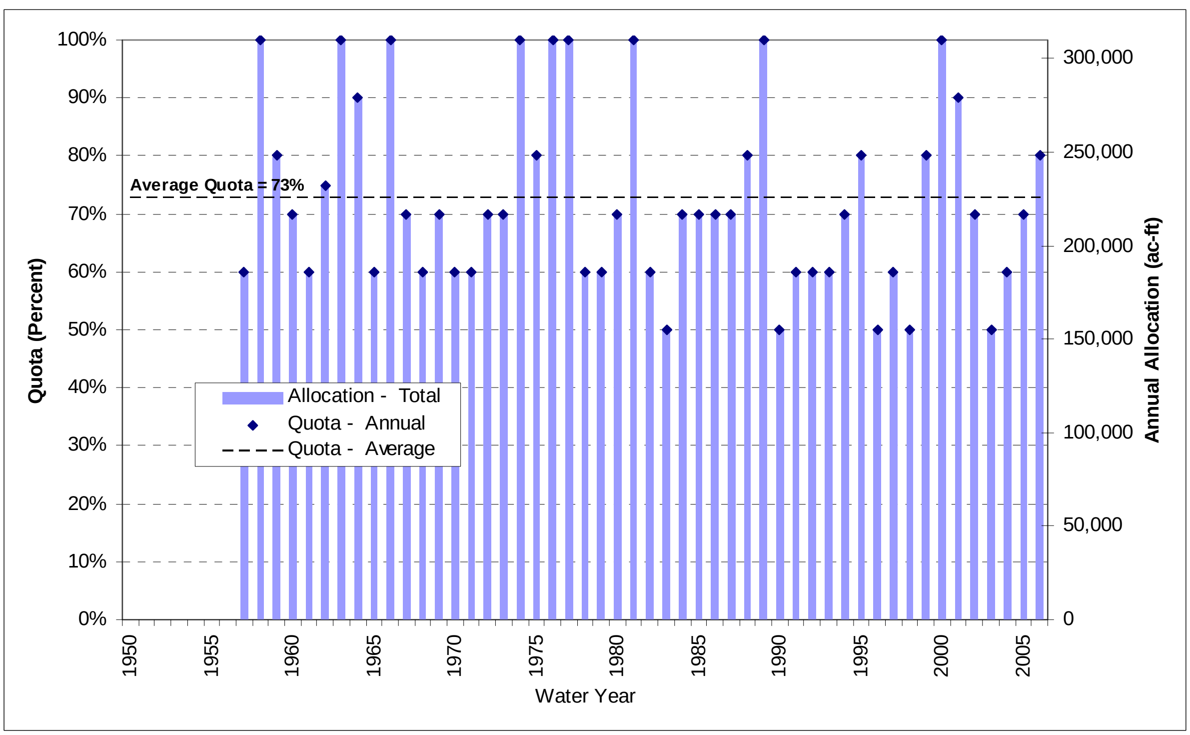


Figure 2. Annual C-BT Quota and Allotment

In addition to direct allocation and direct delivery of C-BT water, District entities may divert return flows that accrue to natural streams within the District. Under Article 19 of the Repayment Contract (United States, 1938), all return flows from the use of C-BT water are "claimed and reserved by the United States for use of the District" to capture, recapture and reuse such return flows. The District Board and Reclamation agreed soon after signing the contract that C-BT return flows would be treated as any other return flows from existing irrigation ditches (Tyler, 1992): in essence, being delivered to downstream users within the District per the priority water rights system.

Demand and Delivery of C-BT Water

When C-BT was first developed and authorized in the 1930s and began operations in the early 1950s, its primary purpose was to supply supplemental irrigation water to agricultural lands within the District. Sugar beets were the primary cash crop at the time, accounting for approximately 40 percent of total irrigated farm revenues on 20 percent of the irrigated area (Bunger, 1937). Alfalfa and small grains made up most of the balance of irrigated area within the District boundaries, with potatoes, beans and corn also irrigated. The supplemental water supplied by C-BT was crucial to the late summer and early fall maturation of the crops, especially sugar beets, at the same time that native river flows significantly decrease. Supplemental water needs of municipal entities were low as significant population increases had yet to happen. Thus, during the initial years of C-BT, a majority of water deliveries were made to agricultural allottees.

Since development of C-BT, the composition of District allottees and their water needs have changed substantially. With the decline of the sugar beet market, the amount of acreage in corn and alfalfa increased substantially. These crops are primarily used as feed for the cattle industry. Both of these crops have a higher tolerance for late-season water shortages, and thus the value of late season supplemental water by irrigation entities decreased, although it still provides substantial benefits to irrigators, especially during dry years. More importantly, both the urban population within the District and the price municipalities are willing to pay for allotment contracts have increased significantly. This has led to a gradual increase in municipal allotment contract ownership and deliveries and a corresponding decrease in agricultural deliveries.

A summary of municipal and agricultural allocation and deliveries is presented in Figure 3. The figure shows the strong decreasing trends in agricultural allocations and deliveries and the increasing trend in municipal allocations and deliveries. Since 1996, municipal ownership has exceeded agricultural ownership. However, agricultural deliveries still typically exceed municipal deliveries. As discussed in subsequent sections, there remains an active rental market in which water allocated to one entity can be rented on a short-term basis to other allottees, typically from municipal allottees to agricultural allottees.

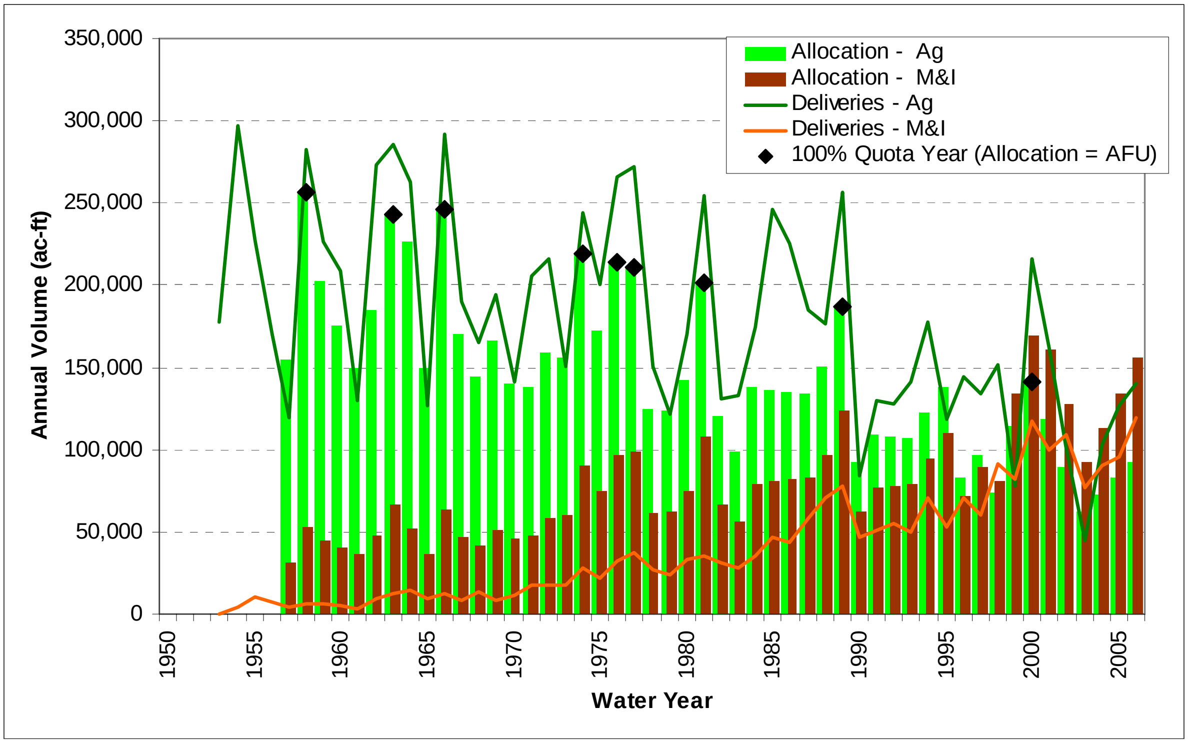


Figure 3. Annual C-BT Allocations and Deliveries

C-BT OPERATIONAL PROGRAMS AND POLICIES

As C-BT has transitioned from an agriculturally-dominated system to a system that serves both municipal and agricultural needs, the District and its allottees have adapted operations and policies to meet changing needs. The allocation system employed by the District to distribute the water provides a reliable, consistent and flexible method to transfer water between water users within the District, which has led to an active short-term rental market. In addition, the District has implemented numerous rules and programs that provide additional flexibility and maximize benefits to all District constituents, including the Annual Carryover Program, the Carryover Capacity Transferability Program (which is discussed as part of the Annual Carryover Program), and the Regional Pool Program. These programs are intended to allow allottees to manage their annual allocations for year-round water demands while promoting temporary leases of municipal water to agricultural users.

Rental Market

The allotment contracts issued by the District specify the quantity, assessment and acre-foot unit definition of water deliveries. However, there is no restriction placed on the point of water delivery except that delivery and use must be within District boundaries. This means that an allottee may choose to transfer all or part of the annual allocation to other lands, areas or services within District boundaries. In fact, the District's rules and regulations state that "allottees may seasonally rent and transfer water from one area of the District to another or from one class of service to another" (District, 1975; in this context "rent and transfer" refers to the temporary seasonal rental of water). This feature of the allotment contracts serves as the basis for the short-term C-BT rental market.

The C-BT rental market has a significant advantage over rental of more traditional native water rights supplies. Under Colorado water law, temporary (especially spot-market) rental of native water rights is difficult because the rental must be approved by the State Engineer's Office (SEO) through the use of Interruptible Water Supply Agreements (Colorado Revised Statues § 37-92-309), which are subject to review by objectors and can be appealed to water court. Permanent changes can only be adjudicated if the change does not injure other vested water rights (Trout, 2004). Typically, historical consumptive use and return flow patterns for both temporary and permanent changes must be maintained to prevent injury to other water rights. This not only limits the amount of water that can be transferred but also increases the transaction time and costs because the transfers often result in water court proceedings. Additionally, because these types of agreements are typically made between individual entities in which the initiating party must find and negotiate with other willing parties, transaction times and costs can be further increased. Despite these restrictions, native water rights rentals and leases are gaining popularity in Colorado due to tightening water supply markets.

The SEO and water court processes are not required to transfer the use or location of C-BT water. The District does have an administrative structure for making the transfer, including Board approval, but the time and monetary requirements are minimal. Most of the rental or lease transactions occur between a willing allottee and a willing water user without the District's involvement. However the District does provide a "clearinghouse" for rental water buyers and sellers, eliminating the need to seek out individual partnerships. These features significantly reduce the transaction time and costs from those required for a native water rights transfer. The ability to transfer is a unique feature of C-BT and has been used as an example by Reclamation of how water bank programs could be used as a "Conservation, Efficiency and Market" tool to meet to meet Reclamation's Water 2025 principals (Reclamation, 2005).

The District does not maintain specific records of rental deliveries. Rather, temporary transfers of water between allottees are booked between accounts, then deliveries to allottees are debited to the account as a whole. However, because most rentals occur when an agricultural allottee rents water from a municipal allottee, the difference in the amount of water delivered and allocated to agricultural allottees can be used to examine the rental market.

Figure **4** presents an annual summary of total agricultural deliveries, estimated deliveries of rental water to agricultural allottees and the percent of total diversions from rental water deliveries. As previously discussed, total deliveries to agricultural allottees has shown a decreasing trend. However, total rental deliveries to agricultural entities show a slight increasing trend, which results in an increasing trend in the percentage of the total agricultural deliveries derived from rental water. Prior to 1980, the average percentage of rental water deliveries was 13 percent, with only two years exceeding 30 percent. Since 1980, the average is 23 percent, with numerous years exceeding 30 percent.

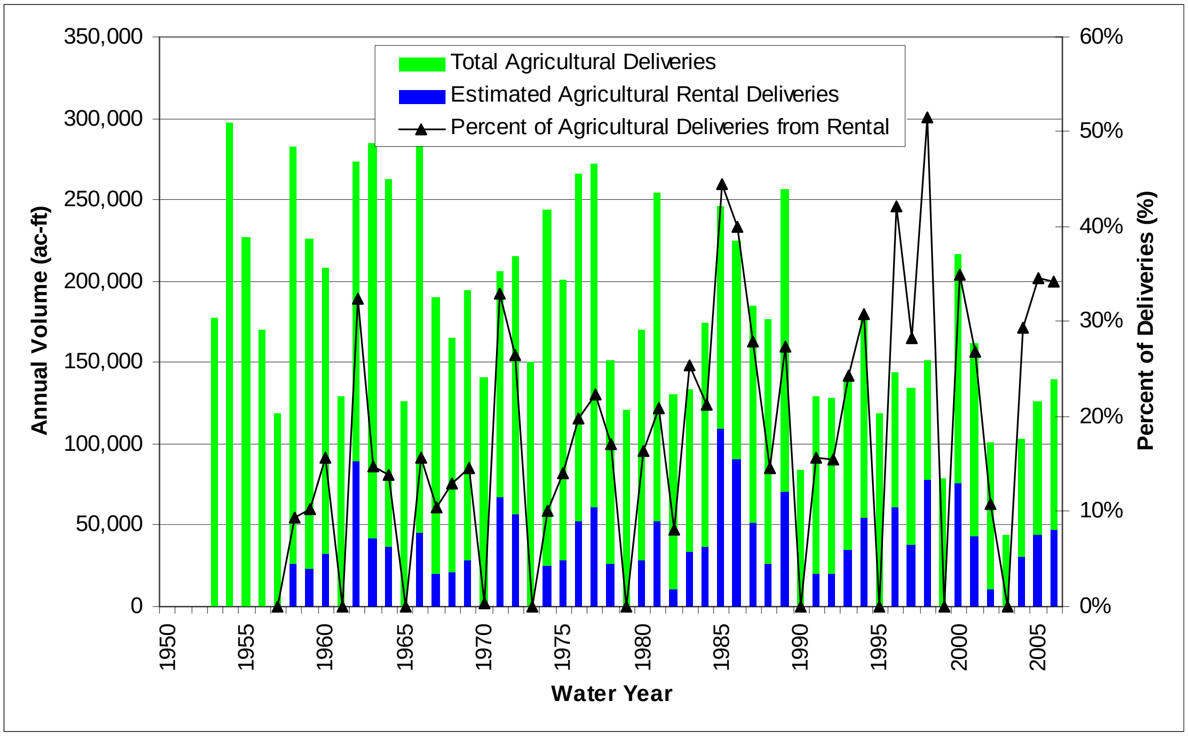


Figure 4. Agricultural Total and Estimated Rental Deliveries

Overall, the analysis shows that the ability to rent water benefits both agricultural and municipal allottees. Agricultural allottees are able to sell allotment contracts to municipal entities and gain instant income from the sale while maintaining the ability to receive at least a portion of their historical deliveries through rentals. By purchasing allotment contracts from agricultural allottees, municipal entities are able to gain a firm supply of water while maintaining the ability to gain an economic benefit through temporary rentals to agricultural entities. However, Figure **4** also shows that during recent drought conditions in 2002 and 2003 there was very little activity in the rental market from municipal to agriculture because municipal allottees required full delivery of their allotted water. In fact, because of the drought, municipal allottees leased a large amount of water from agricultural allottees. This resulted in the lowest total deliveries to agricultural allottees in the history of C-BT. Although this operated exactly as a rental market would expect to operate under these conditions, it does serve as a reminder to the agricultural allottees depending on rental water that little to no rentals will likely take place during drought conditions when supplemental agricultural deliveries are needed most. It may also serve as an indicator of times when growing municipal allottees more fully expand into their C-BT allotments.

Annual Carryover Program

Every allotment contract specifies that any unused allocation shall revert back to the system for subsequent year allocations. Thus prior to 1985, if an allottee had water remaining in his account at the end of the day on October 31, that water would be cancelled from the allottee's account. In 1985, the District Board of Directors implemented a program that allowed entities to carry over any year-end balances to the following year. This program was requested by the municipal and domestic providers to allow unused allocations to be held and controlled for future delivery. The carryover concept provides some flexibility over the management of a given year's allocation as well as an additional water supply when combined with the annual allocation. Some agricultural users were not as enthusiastic about the program because in most years the agricultural users did not have much, if any, balances to carry over at year's end.

The carryover program has undergone significant changes since its initial inception to increase water user flexibility, maintain C-BT's long-term reliability, and enhance the District's water management responsibilities and opportunities. The evolution of the carryover program since its inception is summarized below.

> 1985-1989: Under the initial carryover program the District delivered carryover water for direct use only from April 1 through May 31 of that particular water year. Any water remaining in the carryover accounts after May 31 was cancelled. The District delivered nearly 130,000 acre-feet of carryover water from water year 1987 through 1989. Allottees were allowed to carry over their entire year-end balances for delivery the following year.
>
> 1990: The District Board discontinued the program in water year 1990 to reevaluate the impacts of the program on C-BT and allottees.
>
> 1991-1998: The program was reinstated one year later with several modifications allowing C-BT allottees additional flexibility. Beginning in 1991, the District extended the delivery period for carryover water to July 15. In addition, the District allowed water users to utilize carryover water to fill local reservoirs after June 1. As with the initial program, allottees were allowed to carry over their entire year-end balances.
>
> 1999-2004: In 1998 the District Board further amended the carryover program, extending the delivery period to October 31 to coincide with the end of the water year, adding an assessment charge to those allottees utilizing the program (refunded in the event of a project spill), and providing C-BT allottees with two dates to declare and pay for carryover water. In addition, the carryover quantity was limited to 20 percent of each allottee's AFU ownership.
>
> 2005-present: In 2004, the District Board formalized the carryover program calling it the Annual Carryover Program (ACP). In addition, the Board established the Carryover Capacity Transferability Program (CCTP). The CCTP enables account entity's (AE) requiring additional carryover capacity to obtain it via an annual lease from other AEs. Once the District receives a request, the District will credit the lessee's carryover capacity and debit the lessor's carryover capacity the same amount. The CCTP insures that annual redistribution of carryover capacity will not exceed the total carryover capacity within C-BT. The carryover level set by the Board remains at 20 percent of the total AFU contract amount, or 62,000 acre-feet. However, the Board did authorize a temporary increase in carryover storage capacity to 30 percent for water carried over from 2003 to 2004.

Annual use of the carryover program by allottees is presented in Figure **5**. Until the maximum carryover storage level of 62,000 acre-feet was established by the Board for water year 1999, allottees had steadily been increasing use of carryover storage in the project, with peak use occurring during 1998. The total carryover storage in the project of 146,000 acre-feet represented nearly 50 percent of the total AFU contract amount and approximately 15 percent of total storage in the project. This peak use of carryover storage occurred during a wet hydrologic cycle, when there was low municipal demand for supplemental water, as evidenced by the low amount of carryover deliveries when compared to carryover storage. The most significant issue with this amount of carryover storage in the project was the increased probability of spills from West Slope facilities. Since the carryover cap was implemented in 1999, carryover storage has been much lower, and a much higher percentage of carryover storage has been delivered in the following year. This has resulted in increased rental market activity, even though municipal entities are still recovering from drought.

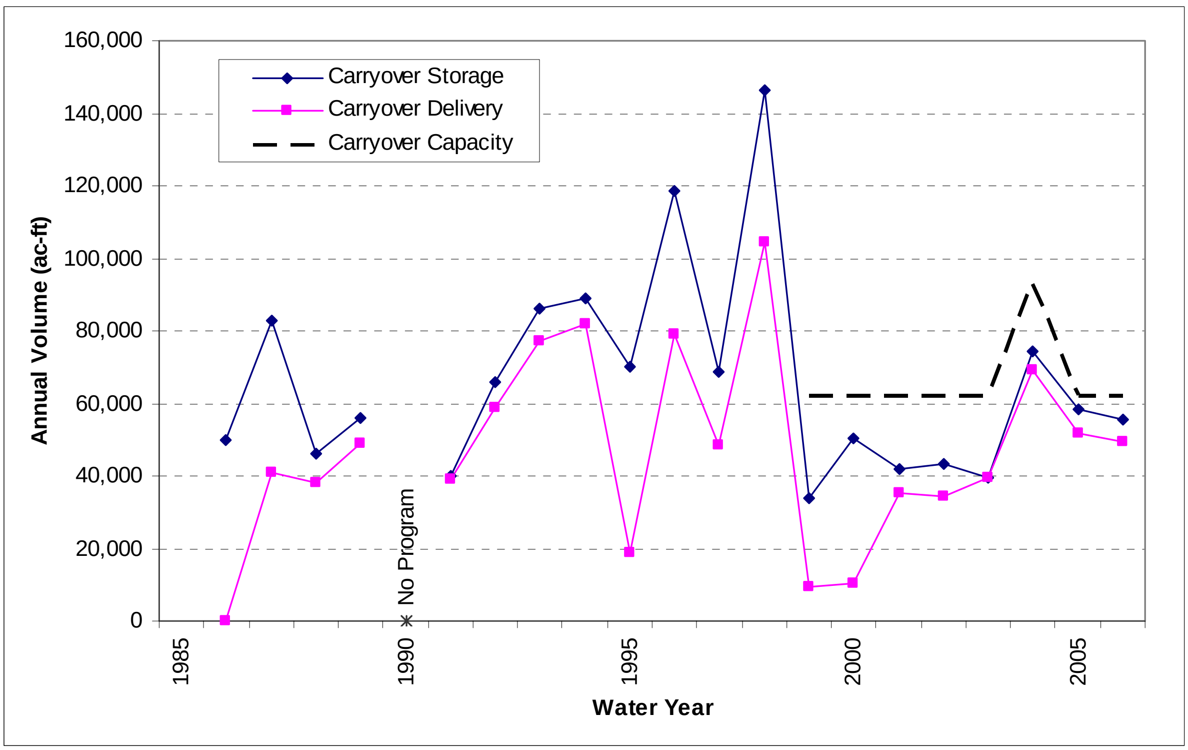


Figure 5. Annual Carryover Storage and Deliveries

<u>Regional Pool Program</u>

The Regional Pool Program (RPP) authorizes the District Board in certain water years the ability to designate C-BT water supplies allocated in a given water year, but not delivered, to be leased to water users within the District during the subsequent water year. The purpose of the RPP is to provide owners of project allotment contracts an additional tool for greater flexibility in the management of their water supplies and to provide potential users of project water supplies greater certainty in meeting their needs for supplemental water. Prior to RPP, any unused allocation was simply left in project storage for subsequent allocations or was transferred into an account as per the carryover program. Under regional pool operations, the unused allocation can be leased by water users within the District prior to its being reallocated. Revenue from the leased water is returned to the lessor.

Although the RPP was approved by the District Board in 2005, the program has not yet operated. This is due to the lingering effects of the drought Colorado has experienced since 2000. RPP rules require that 200,000 acre-feet of unallocated water must be physically available in C-BT storage before the regional pool can operate. This threshold acts as a safety factor to limit any negative, short-term impacts the program might have if amounts in the region pool are of great amounts. The unallocated water in C-BT was 149,000 acre-feet at the end of 2005, and 96,000 at the end of 2006.

The overall objective of the regional pool program is to maintain the beneficial use of C-BT water for supplemental needs within the District. Presently, many municipal and domestic providers own more C-BT units than they may need in a normal water year. Their surpluses, if not leased by these entities, are a valuable resource that can meet demands of other water users.

SUMMARY

As with many irrigated areas in the Western United States, the land within the boundaries of the Northern Colorado Water Conservancy District is experiencing a significant amount of increased water demands from urban development. From the initial development of C-BT and formation of the District to current times, the District Board, staff and allottees are continually discussing and implementing ways to maximize the benefits of C-BT to all of its users. The initial development of allotment contracts provided the flexibility to rent or transfer water within the District with minimum transaction time and costs. More recently, the development of numerous programs and policies which benefit all users, such as the Annual Carryover Program, the Carryover Capacity Transferability Program and the Regional Pool Program, provide the flexibility needed to manage C-BT supplies within multiple water source systems, such as those operated by most municipalities, while maintaining the original full yield and benefits of C-BT.

As District lands continue to be urbanized and the water needs of its constituents change, there will continue to be analysis and fine-tuning of existing programs, as well as development of potential new programs. In addition, the District takes an active role in regional water planning activities. The District currently serves as the managing agency for two water development projects that will provide additional water supplies to municipal entities within the District. By participating in these types of projects and through policies and programs developed throughout its history, the Board hopes to continue the economic viability of agricultural C-BT allotment contract holdings while at the same time develop firm water supplies for in-District municipal entities.

REFERENCES

Bunger, M.E. 1937. *Final Report Colorado Big-Thompson Project Plan of Development and Cost Estimate*. United States Department of the Interior, Bureau of Reclamation. April.

Northern Colorado Water Conservancy District (District). 1963. Meeting Minutes: Special Meeting. March 26.

Northern Colorado Water Conservancy District (District). 1975. *Book II of Rules and Regulations*. July 11.

Trout, Witwer & Freeman, P.C. (Trout). 2004. *Aquiring, Using, and Protecting Water in Colorado*. Bradford Publishing Company, Denver, Colorado.

Tyler, Daniel. 1992. *The Last Water Hole in the West*, *The Colorado-Big Thompson Project and the Northern Colorado Water Conservancy District*. University Press of Colorado, Niwot, Colorado.

United States. 1938. Contract Between the United States and the Northern Colorado Water Conservancy District Providing for the Construction of the Colorado-Big Thompson Project, Colorado. Signed by Oscar L. Chapman, Assistant Secretary of the Interior and Charles Hansen, President, Northern Colorado Water Conservancy District. July 5th.

U.S. Bureau of Reclamation (Reclamation). 1937. Synopsis of Report on Colorado Big-Thompson Project, Plan of Development and Cost Estimate (Senate Document 80). Presented by Mr. Alva B. Adams to the United States Senate, 75th Congress, 1st Session.

U.S. Bureau of Reclamation (Reclamation). 2005. Water 2025*: Preventing Crises and Conflict in the West*.

CITIES VS. AGRICULTURE: REVISITING THE "ALLOCATION STRESS"

François Molle [1]
Jeremy Berkoff [2]

ABSTRACT

Water demand management, or making better use of the water we have—as opposed to augmenting supply—is increasingly proposed as a way of mitigating water-scarcity problems. Moving water away from agriculture to uses with higher economic value is one of the main measures widely seen as desirable. Sectoral “allocation stress” is seen as resulting from the disproportionate share, and inefficient use, of water in the agricultural sector. This apparent misallocation is often attributed to the failure of the government to allocate water rationally.

This paper revisits this commonly-accepted wisdom and examines the nature of urban water scarcity, showing the importance of economic and political factors, shaped by incentives to decision-makers, and sometimes compounded by climatic conditions. It shows that cities' growth is generally little constrained by the competition with agriculture. In general, rather than using a narrow financial criterion, cities select options that go along the “path of least resistance,” whereby economic, social and political costs are considered in conjunction. The question of the allocation stress is thus reframed into an inquiry of how transfer effectively occur and can be made more effective.

INTRODUCTION

Human use of water is reportedly increasing with the growth of population and economic activities. As irrigation diversions rise, they tend to alter and displace natural uses; and as cities and economies expand, domestic, industrial, and in-stream uses also start to impinge on the quantity, quality and timing of water flows, not only for the environment but also for existing and potential agricultural uses. Conflicts amongst and between environmental and human uses intensify, and mechanisms – some planned, many unplanned – emerge to rebalance sectoral allocations. Handling these conflicts and the sectoral re-balancing that is implied are a major concern of the literature.

Sectoral reallocation is seen by many observers as one pillar of water demand management, defined as a “policy that stresses making better use of existing supplies, rather than developing new ones” (Winpenny 1997). It employs a variety of measures, including price incentives, market mechanisms, quotas, subsidies, conservation, treatment, re-cycling, awareness-raising and education (Hamdy et al. 1995; Winpenny 1997). For Gleick (2003) such efforts together

---

[1] Senior Researcher at the Institut de Recherche pour le Développement, France; joint appointment with the International Water Management Institute. Centre IRD, BP 64501, 34394 Montpellier Cedex 5, France. f.molle@cgiar.org

[2] Independent Consultant. 7 Hogarth Hill, London NW11 6AY, UK. jeremyberkoff@mac.com

with decentralization and user participation define a "soft path" approach. Pricing and markets to balance supply and demand have received particular attention (Rosegrant and Binswanger 1994; Bhatia et al. 1994; Easter et al. 1998).

Making better economic use of water implies emphasis on its productivity and the economic welfare to be derived from alternate uses. The World Bank's (1993) policy paper remarks that the value of water differs greatly between agriculture and other sectors, "often indicating gross misallocations if judged by economic criteria … Setting prices at the right level is not enough; prices need to be paid if they are to enhance the efficient allocation of resources." Price and market mechanisms are thus not only presented as a means of cost recovery and demand regulation but also as a way to reallocate water towards higher-value uses. Misallocation is held to be a manifestation of poor water management resulting in economic inefficiency. Rosegrant and Cline (2002) posit that "there is considerable scope for water savings and economic gains through water reallocation to higher-value uses", while Merrett (2003) states that "in the field of water resources management a widely held belief exists that allocation stress is to be found in many parts of the world" (emphasis added). The apparent strength of this argument is predicated on four interconnected assertions:

That agriculture gets the *"lion's share"* of all diverted water resources [70% at world level: much more (80–95%) in developing countries];

1. That agricultural use incurs large wastage, typified by ubiquitous statements to the effect that two-thirds of water delivered to agriculture fails to reach the crop or that irrigation efficiency is typically 30-40 percent;
2. That the value of water in non-agricultural sectors is much higher than in agriculture, typically by an order of magnitude; and
3. That cities are frequently water short, the situation varying greatly depending on climate, resource availability, economic development, etc. Reference is made to cities that ration supplies or fail to guarantee water pressure, either permanently or during dry spells, and to urban areas with precarious or nonexistent water supply facilities.

The juxtaposition of these four statements suggests that water is misallocated, with two corollaries. ***First***, responsibility for this is attributed to the State, since water is generally allocated through centralized management. This assumed failure prompts proposals for pricing and market mechanisms as an alternative (Anderson and Snyder 1997). ***Second***, the contrasting share of water used in agriculture with that in other uses suggests that a relatively limited level of water saving in agriculture would easily make up for the additional needs of the urban sector. This is well exemplified by Gleick (2001) who states that: "The largest single consumer of water is agriculture – and this use is largely inefficient … as much as half of all water diverted for agriculture never yields any food. Thus, even modest improvements in agricultural efficiency could free up huge quantities of water."[3]

---

[3] See similar statements in Winpenny (1997), IRN (2003), Simon (1998), Postel (2001).

The above four statements imply that urban scarcity is in large part due to excessive use of water in the rural sector and to state failure to reallocate water. In other words, irrigation profligacy and bureaucratic inertia help explain urban shortage. Consequently, solutions lie, in part, in demand management in the urban sector but more fundamentally in the improvement of efficiency in agricultural use. Substantial water can be freed and used in higher value uses, reducing the allocation stress for the common good. Water markets may be instrumental in such reallocation and avoid government failure. While not necessarily discarding these arguments, the paper will review the assumptions and the validity of the implicit causal links inherent in the conventional knowledge outlined above. We fill first look at the situation of agricultural use, then question the nature of urban water scarcity, and finally analyze empirical evidence on intersectoral transfers. This will take us to the final section which will attempt to revisit the "allocation gap" and its conventional explicative framework. The paper is anchored in a review of urban-rural water conflicts worldwide, to which the reader is referred for more detail (Molle and Berkoff 2006).

REVISITING THE ALLOCATION GAP

Agricultural Water Use and Productivity

Most water is used by irrigation. To stress that agriculture gets the lion's share implicitly establishes a causal relationship between its large share and the allegedly unfulfilled needs of non-agriculture sectors. But irrigated agriculture is a biophysical process that inherently needs a lot of water, much more water than other consumptive uses. Moreover, agriculture's share is typically dominant when the needs of other activities – apart from those of the environment – have still to compete for comparable amounts. This has been aggravated by the fact that states have invested massively in subsidized irrigation development for a host of (sometimes controversial) socioeconomic and political reasons, reasons which tend to be forgotten with time (see Molle forthcoming). Where other human uses do in fact compete for significant amounts, the balance shifts and irrigation almost always becomes the *residual* human use after other needs have been met. To keep with animal metaphors, the lion's share is perhaps better described as the hyena's share.

Furthermore, irrigation often utilizes flood flows and other marginal sources that cannot provide the level of dependability required by domestic and industrial users. Irrigation thus typically uses a lot of water at times *when* it has no alternative use. In other cases, irrigation and urban networks are disconnected hydraulically and transfers are either impracticable or the costs of storage and/or integration are prohibitively expensive.

Farmers waste water**.** Irrigation's dominant share appears consistent with the conventional belief that farmers waste water: are not large consumers (necessarily) squanderers? The alleged wastage in irrigation has been the subject of a large literature, and decision makers and the media worldwide continue to refer to classical irrigation inefficiency in order to stress alleged mismanagement or to justify interventions of one sort or another. Without entering into the details of this question, it is important to emphasize that (1) waste is relative: if water has no other economic use – is not scarce – then *'wastage'* is of little concern other than for any impacts it has on the environment; (2) even in water short basins, a loss at one point typically flows back to the river or an aquifer and – subject to water quality – can be recycled downstream (Keller et al. 1996; Perry 1999). Efficiency at basin-level is typically much higher than within any individual use; (3) in situations of scarcity, tales of irrigation waste are both misleading and unfair to farmers. Irrigation managers and farmers respond to physical scarcity by optimizing water's value to them – adjusting crops, practices and calendars, and developing conjunctive use by digging wells and installing pumps (Molle 2004b; Loeve et al. 2003); the *"hidden hand of scarcity"* prompts (costly) adjustments that are often overlooked.

Low water productivity in agriculture. Urban water uses usually have higher value to society than irrigation uses, and this is reflected in the priority typically given to domestic – and often industrial – uses both in practice and in law. But this can be presented in misleading terms, either because water does not really constitute a production factor or because like is not compared with like. According to Gleick (2001), for instance, "supporting 100,000 high-tech California jobs requires some 250 million gallons of water a year; the same amount of water used in the agriculture sector sustains fewer than 10 jobs – a stunning difference". He sees a shift from the latter to the former as providing "tremendous gains in efficiency" as if they were really in competition. There is no indication that high-tech industry is ever short of water and it is equivocal to suggest it competes with agriculture.

The Nature of Urban Water Scarcity

Urban water scarcity is often associated with percentages of population not having access to tap water, occurrence of water-borne diseases, or other accounts of poor Water & Supply Sanitation (WS&S) conditions. It is sometimes also linked to alleged constraints to urban sprawl or industrial development. This section examines the nature of domestic urban scarcity and whether economic development is constrained by water being locked up in low-value uses.

Physical and economic water scarcity. Images of "thirsty cities" typifying urban scarcity usually convey a sense of physical scarcity, often made more vivid by dry climatic events. Cities in arid settings understandably run out of water in their immediate vicinity and must opt for costly and distant transfers. Indeed, many cities have developed in the *"wrong"* place and are chronically short (Winpenny 1994). Chennai, Mexico City, Las Vegas and Amman, are cities that have mushroomed despite limited nearby water resources. Even in water-abundant areas, cities outstrip proximate resources when located in upper catchments (e.g. São Paulo, Atlanta, Kuala Lumpur) or in small coastal catchments (e.g. Manila, New York, Boston).

Numerous cities provide water only one or two days per week, conveying a sense of sheer deprivation. Yet, Amman, for example, with its one-day-a-week delivery, still consumes 135 l/c/day, even if Amman East – the poorer area – uses 75 l/c/day (Darmame 2004). Intermittent supply is at least in part due to a concern for limiting the leakage that would result from constant pressure and is resolved by storage at the household level (Decker 2004). Low figures tend to be associated with less-than-ideal water conditions but it is often difficult to distinguish between core needs, comfort, superfluity, excess, and waste. Malé, capital of the Maldives, relies on desalinated water and consumption is 34 l/c/day though supply is 24-hour and reliable (McIntosh 2003) and is less problematic than Chennai with its 68 l/c/day (Brisset 2003).

The causal link between physical water availability and actual supply is loosened by the fact that water-short cities have often been faced with insufficient supply throughout their history, regardless of size.[4] Likewise, there is no shortage of large cities in water-abundant regions with deficient water supply and sanitation systems: e.g. Lagos and Calcutta, with their contaminated sources, dilapidated networks and limited treatment and distribution; or Ho Chi Minh City with only 44 percent of the people having piped water connections to their homes (McIntosh 2003).

This suggests that the root cause is economic rather than physical scarcity, even if the latter may compound the former. Precarious or underdeveloped infrastructure largely reflects a lack of funds and political will. As stressed by Camdessus and Winpenny (2003) "The root cause [of poor water supply to population] is our negligence and our resignation in the face of inequality… All governments, agreeing on the importance of water, subscribe to internationally inspired commitments and undertakings. But their spending performance is at odds with their rhetoric." The capital needed for infrastructural development varies widely but the central question is – unambiguously – who is to pay? Not, where are we going to find the water?, as is also apparent in the World Water Assessment Program (UNESCO 2003) and Anton's (1995) review of water supply in Latin American and Caribbean cities.

<u>Urban scarcity in times of drought</u>. Instances of drought leading to shortage and conflict are allegedly epitomizing allocation problems. They also reflect that allocation is not a problem of average but of extreme events, which reveal how scarcity is shared among users. Are crises due to unrestrained use in agriculture and failure to spare cities by reallocating irrigation water?

There is uncontroversial evidence that the domestic and non-agricultural sectors get priority in times of shortage. For example, shortages in industry and tourism in the "Eastern Seaboard" near Bangkok have been quickly diffused by the implementation of six inter-basin transfers and drilling of 290 artesian wells for short-term relief (Samabuddhi 2005). The California State Water Project cut off farmers in 1991, and the Bureau of Reclamation reduced supplies in the Central Valley by 75 percent (Anderson and Snyder 1997). When Indonesia was hit with a major drought in 1994, residents' wells ran dry but supply to Jakarta's golf courses was ensured so as not to impact on tourism; a similar story unfolded in Cyprus (Barlow and Clarke 2003). Other examples where agriculture suffered first include Amman, Chennai (Ramakrishnan 2002); the Guadaquiver basin in Spain (Fereres and Cena 1997); the Alentejo region in Portugal; Bangkok (Molle 2004b), and Manila (McIntosh 2003).

Except for situations where irrigation holds 'senior' water rights (Colby 1993) or where allocation to agriculture is not reduced in time (crops have already been planted), agriculture clearly stands at the losing end and has to relinquish its share first; shortages only affect domestic use secondarily (and partially), while industries are usually affected last (but many rely on groundwater).

---

[4] See for example Darmame (2004) for Amman, Swyngedouw (2003) for Guayaquil, and Ducrot et al. (2003) for São Paulo.

Industries and urban economic activities. Discussions of urban scarcity generally focus on domestic WS&S services, with little reference to stress undergone by industries, despite distinctions between the two sectors. *First*, industries generally need secure and continuous supply of high-quality water. They thus tend to exploit deep aquifers wherever feasible (e.g. 90 percent of industries in Bangkok). *Second*, the industrial sector represents an interest group that is affluent, powerful and closely linked to the highest levels of political and bureaucratic apparatuses.

Whether longer-term investments in services and industry are constrained by water remains perhaps a matter of debate. Very high water-consuming industries, such as aluminum, are unlikely to settle in water-short areas, and suggestions have been made that water-intensive industries should be moved e.g. inland from coastal China (Chan and Shimou 1999). Even so, there is little evidence that cities and industries are seriously constrained in their growth by water. By and large, industries that offer to create jobs and increase business taxes are unlikely to be denied preferential access to municipal water. Alternatively, they abstract groundwater regardless of whether this is sustainable or not. Ramakrishnan (2002), for example, describes the drastic restrictions on water supply in Chennai but, at the same time, reports that the Chennai Petroleum Corporation's demand for an additional 15,000 m^3/day needed for its expansion project has been readily agreed upon.

Simon (1998) notes that: "Ironically, the areas of the world with the fastest growing populations are also the areas with already severe water problems, and the shortage will get much worse." This serves to show that lack of water does not hinder expansion although growth outpaces financial capacity to expand supply networks. This contrasts starkly with the situation in many western countries where water is a prerequisite to expansion: many cities in the Western US, for example, require developers to prove their right to adequate provision of water before construction begins (Lund and Israel 1993).

The political economy of urban water supply. Given the prominence of the financial and political dimensions of urban water scarcity, the central question becomes: how do such investments become a priority? Several documents (Rijsberman 2004; UNESCO 2003; Smets 2004) give varying estimates of the financial resources needed to meet MDG targets or bring urban WS&S services up to standard. These amounts are substantial but not beyond the financial capacity of consumers, countries and international institutions. Incentives to decision makers, the political clout of a given city, and public mobilization all matter in defining priorities.

In Europe, in historic times, extension of WS&S facilities beyond the affluent can be attributed to a combination of the hygienist movement, a perceived "threat from below" (Chaplin 1999) and/or the need "to preserve order, cleanliness and a healthy workforce" (Goubert 1986). As early as the mid-18th century it was recognized that "prevention of further environmental degradation was cheaper and more effective … than continuing with expenditure on poor relief" (Chaplin 1999).

The capacity of city managers and politicians to fund investment is also closely linked to a city's location within the state/region/nation, both in geographical and in political terms. Capital cities are more likely to get access to public funds (e.g. Mexico: Connolly 1999). How taxes are distributed amongst administrative layers – central to local government – is also crucial.

Swyngedouw's study (2003) on Guayaquil and Bennett's (1995) on Monterrey show that the distribution of power determined whether investments were made or not, who paid for them, and what sources of water were to be tapped. Some cities attract foreign subsidies (e.g. EU funds for Athens) or benefit from geopolitical considerations (e.g. Amman) or broad reconstruction efforts (e.g. Phnom Penh). If society is receptive to privatization, the financial burden can be shifted to users, as in the UK.

In general, therefore, and notwithstanding that water projects are more or less costly, the state of the WS&S systems depends far more on political and financial circumstances than on competition with other sectors for the basic water resource.

Inter-Sectoral Transfers in Practice

Types of transfer mechanisms. Inter-sectoral water transfers do happen in practice and take several forms. *Temporary transfers* typically occur during a drought. *Permanent transfers* occur when a source of water already tapped by several users and is diverted to the benefit of a city. Such transfers can be gradual, often first amounting to a limited percentage of the source of origin. Its effects tend to be diffuse and unidentifiable since the source continues to provide a large share of water to other users. But they can also be *outright*, and if they amount to a large part or all of an existing source (e.g., the conversion of - irrigation reservoirs to municipal use in China) then they are likely to be problematic if no compensation is paid.

Transfers can also be categorized based on the mechanisms utilized in their implementation, with three apparent main types.[5] A first type of transfers occurs through the transfer of *formal rights* to the use of water. These are typified by practices in developed countries, notably the west US, Australia and other arid regions but increasingly also in the eastern US and other developed countries. Formal rights can in principle be transferred in a free market with the price reflecting market conditions either in real time, or over a longer period (a season or year), or permanently. Markets in *informal rights*, in contrast, develop spontaneously but generally involve farmer-to-farmer sales rather than inter-sectoral sales. An exception is the conversion of irrigation wells to tanker operations in Amman and some cities in India, which represents a significant case of an unregulated market transaction from agricultural to urban use.

Administrative decision has been by far the most important mechanism for transferring water from one use to another, both historically in developed countries and to this day in developing countries. *Formal administrative decisions* are taken by a national, provincial/state or basin entity depending on the functions assigned to each under the constitution or in law. They involve varying degrees of consultation between the interested parties (e.g. Seville, Tsingtao, etc.). Direct expropriation is problematic for any government, even an authoritarian one, especially in contexts where the local economy revolves around irrigated agriculture. This is true even if no

---

[5] The potential of water pricing as a means for eliciting reallocation from agriculture to other sectors has also been emphasized by some economists but is now widely considered as negligible (Savenije and van der Zaag 2002; Cornish and Perry 2003; Hellegers and Perry 2004; Molle and Berkoff 2007), a point also recently acknowledged by the World Bank (2003).

formal rights are held. The buying out of agricultural wells around some cities (Chennai) is an example of outright and total reallocation of minor sources with appropriate compensation.

Negotiations can include financial compensations and/or efforts by the city to reduce its losses or its consumption. El Paso, for example, obtained water from the Rio Grande on condition that it reduce per capita consumption, recycle sewage water and eliminate leakage (Earl 1996). Well known agreements between the Imperial Valley Irrigation district and the Southern California Metropolitan Water Authority (CGER 1992), or between Delhi and the Upper Ganga irrigation scheme, included lining of irrigation canals by the cities.

When formal administrative decisions to transfer water are taken unilaterally, they merge imperceptibly into informal *transfers by stealth*. This may occur as a result of investment decisions (as in Hyderabad) or management decisions (as in Manila), or development decisions (as in the occupation of tanks in Bangalore or the conversion of irrigated land to urban use as in many expanding cities). Transfers by stealth by definition do not allow for compensation. Some transfers are explicit and obvious to observers (e.g. large pumping stations), not least to the farmers; others are more surreptitious, like when there is a long distance between the point of diversion and the downstream farmers/users. Groundwater abstraction by a city, or reappropriation of water through gradual encroachment upon irrigated land (e.g., Manila, Lima, Bangkok, Cairo) can pass virtually unnoticed at first.

In support of such transfers it is sometimes argued that farmers, who typically paid only a small fraction (if any) of the costs of irrigation, cannot object if the state subsequently withdraws a part of the water allocated to them. This has less force once the value of water is capitalized in land prices. Another argument is that the real costs to farmers of partial “expropriation” may be less than appears at first sight, given the room for adjustment in many irrigation systems and the fact that the *“hidden hand of scarcity”* elicits changes in behavior and factor use.

Predictably, cities do not publicize widely their water projects, minimize their impacts, and avoid talk of compensation. Analyses of conflicts (see above) show that nonagricultural uses almost always get priority but also that the crux of the matter is not so much the average amount diverted to cities but *what this share becomes at times of shortage*. When a drought occurs and the impact felt becomes critical, it is always possible to naturalize crises, blaming it on climatic change, El Niño, "the rain gods" (The Hindu 2003), or bad luck. Controversial transfers from the Veeranam tank to Chennai, from the Kinjhar lake to Karachi, or from El Cuchillo dam to Monterrey, all officially claim to use “only excess water” and to "preserve existing uses", despite evidence to the contrary.

<u>Environmental impacts of transfers</u>. While cities gradually displace agriculture, agriculture has to adjust and respond to the squeeze. Part of the response comes through an increase in efficiency, notably at the basin level where a greater part of return flows is reused and depleted, or through the use of wastewater instead of freshwater. In many cases, however, irrigation compensates this reallocation by taking more water from the environment, directly "displacing nature".

Cities dispose of 80 percent of the water they divert as wastewater. Only 10 percent of the effluents from cities in developing countries are treated (Joyce 1997). The growth of urban/industrial needs plays out not only in terms of transfer of equivalent volumes of water but also in terms of reduction of the stock of usable water by rendering part of it unfit for human, and even agricultural, use. A good example of this is provided by Janakarajan (2003) who describe the impact of tanneries on the Palar river basin, in Tamil Nadu. Tanneries use many toxic chemicals and generate heavy pollution, to the point that downstream farmers have refused to use the river. This has also happened in the Damodar river (India), in South Africa, because of mines, and in the Huai river basin (China) because of paper industries and tanneries (Postel 1999). It must be noted, however, that agriculture activities are now increasingly contributing to turning surface water and groundwater unusable for cities.

Tapping groundwater is the easiest solution because it generally relies on individual or corporate investments (as opposed to public ones), it is spatially spread with little need for infrastructure, and it frequently penalizes constituencies that often have little voice (nature and the next generations). That between 1.5 and 2 billion humans in the world, of which one billion urban dwellers in Asia (Foster 1999), rely on groundwater for domestic consumption gives an idea of how widely this solution has been resorted to. The hidden costs are becoming increasingly apparent and include:

Reduction in available stocks, drop in the water level and resulting increase in pumping depth and related expenditures. Other used are pumped out.

- Land subsidence in cities like Mexico City, Manila, Jakarta, Cangzhou, Beijing, or Bangkok (a third of the city is now under sea level). Subsidence affects not only buildings and roads but also the future water storing capacity of the aquifer itself.
- The quality of groundwater almost everywhere. Realization of its extent is increasing in proportion to the number of measures and investigations being carried out (Sampat 2000).
- Salinity intrusion due to the overdraft of coastal aquifers rendering water unfit for both domestic and agricultural use, in cities such as Tel Aviv, Lima, Jakarta, and Dakar.
- The drying up of springs and wetlands fed by groundwater flows that are affected by the lowering of watertables (e.g. Azraq wetland in Jordan.

The overall picture is that if cities have generally found ways to increase their water supply, this has often been in an unsustainable and damaging way, displacing agriculture and nature, and critically impacting water quality and the amount of usable water.

Reallocation stress: political and social costs. In a situation of competition, cities will generally have to re-appropriate water already used, allocated or "owned" by other users, generally agriculturalists or nature itself, and this inevitably generates stress. Such transfers appear to breed political tension irrespective of the mechanism used. Political stress is generated in proportion to the political clout of the constituencies that stand to lose in the transfer (the water users in the first place but also surrounding communities). Urban industrialists generally command considerable power over politicians. Conversely the cost of doing nothing, or little, is less when urban populations affected by prevailing poor conditions of WS&S are also voiceless. As the Camdessus Report put it: "with the mass of people not serviced politically weak or disempowered, it is tempting to postpone spending on maintenance and periodic replacements, likewise on investments with a long gestation period.”

The difficulty of acquiring more water is also dependent on the political structure and administrative boundaries. A transfer within the same state, region or district – whatever the local structure – is easier to handle. Those involving different provinces/states in federal entities are more difficult and depend on the respective powers vested in the central government and the states, and on the clarity of their roles (see Barajas (1999) on Mexico and Richards and Singh (2002) on India).

It is tempting to circumvent political intricacies with a proposal to choose transfers or supply augmentation based on a full cost assessment. But in practice, decision-making incorporates wider aspects of the local political economy: social, transaction, political, and sometimes environmental costs attached to the various demand – or supply – oriented options; the nature of the possible source of funding; the degree of mobilization/pressure by various constituencies; pre-existing customary (or other) rights and water uses (Howe et al. 1990). Eventually, decision makers tend to follow the *“path of least resistance”* (Kenney 2004), which may differ from what a more narrow sectoral rationality might, *prima facie*, suggest to be the way forward. Of course while pursuing a mere economic logic is likely to be detrimental to equity, unchecked centralized and obscure decision making may favor costly options that only benefit a few constituencies. Political mediation has to follow a narrow path between public and private interests.

THE ALLOCATION GAP: CONCLUSIONS AND PERSPECTIVES

The allocation gap revisited

Industrial and domestic water use is often believed to be constrained by the excess amount of water used in agriculture. Since irrigation is usually inefficient both in technical (it incurs many losses) and economic terms (low value per cubic meter), this situation creates an "allocation gap" that amounts to an economic loss to society. This paper has challenged the magnitude of this gap and given alternative analyses of the nature of urban water scarcity, distinguishing between municipal and industrial uses, and between short term and long term reallocation.

Temporary reallocation often occurs in times of drought. Short-term crises may be partly due to climatic variability but they are compounded by lax management of security stocks: except for situations where irrigation holds 'senior' water rights or where allocation is not reduced in time (crops have already been planted), agriculture clearly stands at the losing end and has to relinquish its share first; shortages only secondarily (and partially) affect domestic use, and then industries. On the long run, cities also appear little constrained by the competition of agriculture. While suboptimal WS&S conditions in many cities, particularly in arid climates, point to a lack of water, this situation is mainly due to insufficient investments that have economic and political roots, and eventually reflect incentives to decision-makers for prioritizing such investments. Industries, in turn, either rely on groundwater or receive priority allocation justified by their economic importance, and contribution to local tax base and employment.

Contrary to received wisdom on state failure, states do give priority to cities and industries, transfers *do* occur, and the alleged economic benefits waiting to be realized are often much inflated. Thus, in both the short and long term, farmers are "losing out" (Winpenny 1994), urban interests are getting the "upper hand" (Lundqvist 1993), and "without a doubt, cities will continue to siphon water away from agriculture" (Postel 1999).

Yet, it is widely believed that increased supply to cities could enhance economic output, with scarcity attributed to excessive allocation to agriculture (see introduction). In the ADB's (2000) view, for example, "Irrigation is particularly voracious, accounting for up to 80 percent of water demand in hot dry regions … Major obstacles to the rational reallocation of water among users … are the legal and regulatory constraints on water transfers and, in many countries, the complex systems of water rights that inhibit the free movement of water as an economic good." Why does the literature appear to place such emphasis on the gains from reallocation, if these are in fact quite limited? The oft-stated problem of sectoral allocation as a significant hindrance to economic development is perhaps only a hasty generalization of the situation in the Western US (where the prior-appropriation doctrine has tended to lock up water use in low-value uses) to contexts where centralized management has by and large ensured inter-sectoral reallocation. This may also reflect the ideological inclination of those advocating markets as an allocation mechanism (Bauer 2004).

The question of the allocation gap was therefore reframed into an inquiry of how transfers effectively occur. While cities by and large succeed in accessing increasing resources this has often not been optimal in economic, social or environmental terms. Water has often been overabstracted from aquifers, taken away from ecosystems or from agriculture (which, in turn, has often displaced nature too), or from distant sources at a high cost. Economic rationality has often been abused but decision making reflects wider social and political considerations that are not easily captured by valuation techniques, as well as the distribution of political power within society. Eventually, all things being considered, cities select the path of least resistance. While "politics" is often construed in a negative sense because of its rent-seeking and pork-barrel dimensions, these aspects must be checked by democratization of decision making and increased public access to data, so that political mediation becomes an effective way of balancing antagonistic interests and world views, rather than a way to further vested interests.

Somewhat ironically it seems that it is where water rights are formally defined and enforced – and thus liable to transaction- that reallocation is problematic. Where water is centrally allocated reallocation occurs to bridge the allocation gap, but to the detriment of those deprived of the resources. The crux remains to rationalize and compensate transfers. In both cases the necessity - and difficulty- to account for all third-party and environmental impacts remains a challenge endlessly renewed by climate variability and shifting patterns of power.

How to improve reallocation of water

The option of water markets. Small-scale water markets have long existed in many arid countries. User sharing a common source (spring, qanat, etc) occasionally swap, lend, borrow, sell or buy water turns in order to fine-tune supply to time-specific individual demands. This also occurs in large-scale irrigation systems (e.g., warabandi in Pakistan and India). At these scales, transaction costs are minimized because users know each other (Reidinger 1994), can readily communicate, and transfers are across short distances and socially controlled. The extension of market mechanisms on a larger scale has been much less frequent and more difficult (Livingston 1995). Markets in the Western US are limited by constraints that reflect the crucial nature of water for life and the complexity of the hydrological cycle, which invariably generates third-party impacts (Dellapenna 2000; Kenney 2003; Libecap 2003). In the Colorado-Big-Thompson system market transactions have allowed smooth and gradual transfer partly because trading is occurring only within the system and because the water district holds the right to all return-flows (Howe and Goemans 2003). Water markets in Australia (Turral et al. 2004) or in Chile (Bauer 2004) remain limited in terms of volume traded but reallocation has performed reasonably well, although third party impacts and speculative behavior reduce their efficiency. China also started experimenting with inter-provincial trading of water but soon discovered the implications in terms of return-flow and environmental impact (Fu and Hu 2002).

Positive experience seems to be confined to countries with a strong legal, institutional and regulatory background and relatively wealthy stakeholders. Proposals for their adoption in countries where hydrologic data are scarce, physical infrastructure is lacking, and states have weak monitoring and enforcement capacity, are unrealistic. One may question why states that have allegedly failed to allocate water efficiently would be capable of creating the numerous preconditions and safeguards needed to ensure fair and transparent markets (Molle 2004a). It is doubtful that fully-fledged markets will constitute a major tool for the reallocation of water in the near future, most especially in developing countries (Frederik 1998; Dellapenna 2000; Livingston 1995; Meinzen-Dick and Appasamy 2002).

Contingency planning and temporary transfers. Conflicts between cities and agriculture surface primarily during water crises, when the share diverted by the former rises from a low average to a much larger share. This implies that permanent transfers of rights are often not necessary (Savenije and van der Zaag 2002). Agricultural and non-agricultural uses can usually coexist, if shares are expressed in terms of average. Emphasis should be placed on the design and provision of mechanisms to compensate farmers for losses and deprivation that *will* occur in times of shortage. This is easier to achieve than permanent expropriation of agricultural water, while allowing for a more efficient use of water.

State or cities which tap other sources prefer to present (and obscure) the impact of diversions in average terms. Technical agencies, too, are reluctant to engage in debates that would reveal that domestic supply is not fully reliable and undermine their professional legitimacy. Yet drought-management strategies are needed to provide an early warning of possible shortages and as a predefined set of actions for different conditions (Frederiksen 1992). If priorities are well-established and transparent information provided, negotiations can prepare for such arrangements and avoid the outcry and political crises that often accompany severe water shortages.

Participation and environmental justice. The displacement of agriculture and nature by growing cities/industries as well as their indirect impact through their contamination of freshwater have heavy social, environmental, and health costs. The magnitude and the distribution of these externalities is very much a reflection of the governance structure of the society. The "stamina" and the mobilization of the "people living downstream" (Narain 1999), and the political space offered to disenfranchised groups to voice their concern are paramount. They ultimately determine whether externalities are recognized and internalized, but also who pays for that. Because WS&S projects usually involve large outlays of money, decision-making remains largely centralized and technology-oriented. A shift from supply-oriented paternalistic development to process-oriented approaches leading to “informed consent” (Delli Priscoli 2004) is materializing only slowly. Deliberative development enables a better definition of social choice but can only develop in a political configuration where redistribution of power is possible.

REFERENCES

Abernethy, C.L. 2005. Financing river basin management. In Svendsen, M., Merrey, D. J., and Shah, T. (eds.): *Irrigation and river basin management: Options for governance and institutions*. CABI, Wallingford.

ADB (Asian Development Bank). 2000. *Water in the 21st century*. Annual report 1999. Manila.

Anderson, T. L.; Snyder, P.S. 1997. Priming the invisible pump, Political Economy Research Center: Montana, US.

Anton, D. J. 1995. *Thirsty cities: urban environments and water supply in Latin America*. Ottawa, IDRC. 180p.

Barajas, I. A. 1999. *Interregional transfer of water in Northeastern Mexico: The dispute over El Cochilo*. Knowledge base of the World Commission on Dams. www.dams.org

Barlow, M.; Clarke, T. 2003. *Blue gold*. New Delhi: LeftWord Books.

Bauer, C. J. 2004. *Siren song: Chilean water law as a model for international reform*. Washington: Resources for the Future. 173p.

Bennett, V. 1995. *The politics of water: Urban protest, gender, and power in Monterrey, Mexico.* Pittsburgh: University of Pittsburgh Press.

Bhatia, R.; Cestti, R.; Winpenny, J. 1994. *Policies for water conservation and re-allocation: good practice cases in improving efficiency and equity.* World Bank Technical Paper. Washington, D.C.: World Bank.

Brisset, S. 2003. *L'alimentation en eau potable d'une métropole Indienne (Chennai): Une lutte coûteuse pour quel développement?* Festival International de Géographie Saint-Dié-des-Vosges, France.

Camdessus, M.; Winpenny, J. 2003. Financing water for all. Report of the World Panel on Financing Water Infrastructure. www.wsscc.org/download/Camdessus%20document.doc

CGER. 1992. California’s Imperial Valley: A “win-win” transfer? In *Water transfers in the west: efficiency, equity, and the environment.* The National Academy of Sciences.

Chan, R. C. K.; Shimou, Y. 1999. Urbanization and sustainable metropolitan development in China: Patterns, problems and prospects. *GeoJournal* 49: 269–277.

Chaplin, S. E. 1999. Cities, sewers and poverty: India’s politics of sanitation. *Environment and Urbanization* 11(1): 145–158.

Colby, B. G. 1993. Reallocating water: Evolving markets, values and prices in the Western United States. *Water Resources Update*. Universities Council on Water Resources, Issue No. 92: Water Pricing and Marketing.

Connolly, P. 1999. Mexico City: our common future? *Environment and Urbanization* 11(1): 53–78.

Cornish, G. A.; Perry, C. J. 2003. *Charging for irrigation services: Lessons from the fields*. Report OD 150. Wallingford, UK: HR Wallingford.

Darmame, K. 2004. *Gestion de la rareté: Le service d'eau potable d'Amman entre la gestion publique et privée*. Amman, Jordan: Mission Régionale Eau-Agriculture; Colombo: International Water Management Institute.

Decker, Christian. 2004. Managing water losses in Amman's renovated network: A case study. Paper prepared for the International Water Demand Management Conference, June 2004, Dead Sea, Jordan.

Dellapenna, Joseph W. 2000. The importance of getting names right: the myth of markets for water. *William and Mary Environmental Law and Policy Review* 25 (317–377). 2000.

Delli Priscoli, J. 2004. What is public participation in water resources management and why is it important? *Water International* 29(2): 221–227.

Earl, R.A. 1996. Sunbelt water war: The El Paso-New Mexico water conflict. *The Social Science Journal* 33(4): 359–380.

Easter, K. W.; Rosegrant, M. W.; Dinar, A. (eds.). 1998. *Markets for water: Potential and performance*. Boston: Kluwer.

Fereres, E.; Cena, F. 1997. Social benefits and environmental constraints of irrigation in an era of water scarcity. In *Water: Economics, management and demand*, ed. Kay, M.; Franks, T.; Smith, L. London, UK: E & FN Spon. pp. 128-136.

Foster, S. 1999. The interdependence of groundwater and urbanisation. In *Proc. of the 9th Stockholm Water Symposium*. "Urban stability through integrated water-related management," August 9–12, Stockholm. pp. 125–138.

Frederiksen, H. D. 1992. *Drought planning and water efficiency implications in water resources management.* Washington, D.C., USA: World Bank. iii, 37p. (World Bank Technical Paper No.185)

Fu, C.; Hu, Z. P. 2002. The practice on water rights allocation and trade-off in China. Paper presented to the RiverSymposium 2002, September 2000, Brisbane. archive.riverfestival.com.au/2002/files/symposium/FuC.doc

Gleick, P. 2001. Making every drop count. *Scientific American*, February 2001.

Gleick, P. H. 2003. Global freshwater resources: Soft-path solutions for the 21st century. *Science* 302: 1524–1528.

Goubert, J. P. 1986. *La conquête de l'eau*. Paris : Robert Lafont. Collection « Pluriel », 300p.

Hamdy, A.; Abu-Zeid, M.; Lacirignola, C. 1995. Water crisis in the Mediterranean: Agricultural water demand management *Water International* 20(4): 176–187.

Hellegers, P.; Perry, C. J. 2004. *Water as an economic good in irrigated agriculture: Theory and practice*. The Hague: Agricultural Economics Research Institute (LEI). 152p.

Howe, C. W.; Goemans, C. 2003. Water transfers and their impacts: Lessons from three Colorado water markets. Journal of the American Water Resources Association, Oct 2003.

Howe, C. W.; J. K. Lazo; K. R. Weber. 1990. The economic impacts of agriculture-to-urban water transfers on the area of origin: A case study of the Arkansas River in Colorado. *American Journal of Agricultural Economics* December:1200–1204.

Janakarajan, S. 2003. Water pollution and groundwater depletion multi-stakeholders' dialogue as a key for finding ways forward. Paper presented to the Seminar on Water, Centre for Economic and Social Studies, Hyderabad.

Joyce, Stephanie. 1997. Growing pains in South America. *Environmental Health Perspectives*, Volume 105, Number 8 August 1997. http://ehp.niehs.nih.gov/docs/1997/105-8/focus.html

Keller, Andrew; Keller, J.; Seckler, S. 1996. *Integrated water resources systems: Theory and policy implications.* Research Report 3. Colombo, Sri Lanka: International Irrigation Management Institute, 15 p.

Kenney, D. 2004. Personal communication. By e-mail.

Kenney, D. 2003. Water allocation and management in the western United States: An overview. Paper presented to the International Working Conference on Water Rights: Institutional options for improving water allocation. Hanoi, Vietnam, February 12–15, 2003.

Libecap, G. 2003. *Transaction Costs and the Reallocation of Water Rights from Agriculture to Urban and Environmental Uses.* Working paper, Karl Eller Center, University of Arizona.

Liu, Bin. 2003. Water rights in China. Paper presented to the International Working Conference on Water Rights: institutional options for improving water allocation. Hanoi, Vietnam, February 12–15, 2003.

Livingston, M. L. 1995. Designing water institutions: Market failures and institutional response. *Water Resources Management* 9(3):203–220.

Loeve, R.; Hong Lin; Dong Bin; Mao, G.; Chen, C. D.; Dawe, D.; Barker, R. 2003. Long term trends in agricultural water productivity and intersectoral water allocations in Zhanghe, Hubei, China and in Kaifeng, Henan, China. In *ICID Asian Regional Workshop, Sustainable Development of Water Resources and Management and Operation of Participatory Irrigation Organizations, November 10–12, 2003, Taipei. Vol.1*. Taipei, Taiwan: ICID. 367–380.

Lund, J. R.; Israel, M. 1993. Water transfers in water resource systems. *Journal of Water Resources Planning and Management* 121(2): 193–204. 314

Lundqvist, J. 1993. Rural water for expanding cities: A case study on water re-allocation in Tamil Nadu, India. Paper presented to *the International Conference on Environmentally Sound Water Resources Utilization*, 8–11 November 1993, Bangkok, Thailand.

McIntosh, A.C. 2003. *Asian water supplies: reaching the urban poor*. Manila: Asian Development Bank and International Water Association.

Meinzen-Dick, R.S.; Appasamy, P.P. 2002. Urbanization and intersectoral competition for water. In *Finding the source: The linkages between population and water.* Washington DC: Woodrow Wilson International Center for Scholars. pp. 27–51.

Merrett, S. 2003. The urban market for farmers' water rights. *Irrigation and Drainage* 52(4):319–326.

Molle, F. 2004a. Defining water rights: By prescription or negotiation? *Water Policy* 6(3): 207-227.

Molle, F. 2004b. Technical and institutional responses to basin closure in the Chao Phraya river basin, Thailand. *Water International* 29(1): 70–80.

Molle, F. Forthcoming. Why enough is never enough: The societal determinants of river basin closure. *International Journal of Water Resource Development.*

Molle, F; Berkoff, J. 2006. Cities versus Agriculture: Revisiting intersectoral water transfers, Potential gains and Conflicts. Colombo, Sri Lanka: IWMI. (Comprehensive Assessment Research Report 10). http://www.iwmi.cgiar.org/Assessment/Publications/research_reports.htm

Molle, F., Berkoff, J. (eds.) 2007. Irrigation water pricing policy in context: Exploring the gap between theory and practice. Comprehensive Assessment of Water Management in Agriculture. Wallingford, UK: CABI. Forthcoming.

Molle, F; Mamanpoush, A.; Miranzadeh, M. 2004. *Robbing Yadullah's water to irrigate Saeid's garden: Hydrology and water rights in a village of central Iran.* IWMI Research Report No 80. Colombo, IWMI.

Narain, S. 1999. We all live downstream: Urban industrial growth and its impact on water systems. In *SIWI*, *Urban stability through integrated water-related management*: *Proceedings - The 9th Stockholm Water Symposium, Stockholm, Sweden, August 9–12, 1999.* Stockholm, Sweden: SIWI. pp.75–83.

Perry, C.J. 1999. The IWMI water resources paradigm: Definitions and implications. *Agricultural Water Management* 40(1): 45–50.

Postel, S. 1999. *Pillars of sand.* New York, NY: W.W. Norton & Co.

Postel, S. 2001. Growing more food with les water. *Scientific American* February 2001.

Ramakrishnan, N. 2002. Chennai water lorry operators on the back foot. *The Hindu Business Line*. August 01, 2002.

Reidinger, R. 1994. Observations on water markets for irrigation systems. In Water policy and water markets, ed. Guy Le Moigne, K. William Easter, Walter J. Ochs, Sandra Giltner. 65–78. World Bank, Technical Paper No 249.

Richards, A.; Singh, N. 2002. Inter-state water disputes in India: Institutions and policies. *International Journal of Water Resources Development* 18(4): 611–625.

Rijsberman, F. 2004. The water challenge. Copenhagen Consensus Challenge Paper. Fifth draft. http://www.copenhagenconsensus.com/Default.asp?ID=228

Rodríguez, J. E. Mestre. 1997. Case Study VIII - Lerma-Chapala Basin, Mexico. In *Water pollution control - A guide to the use of water quality management principles.* WHO/UNEP.

Rosegrant, M. K.; Cline, S. 2002. The politics and economics of water pricing in developing countries. Washington D.C.: International Food Policy Research Institute. Draft note.

Rosegrant, M.; Binswanger, H. 1994. Markets in tradable water rights: potential for efficiency gains in developing country water resource allocation. *World Development* 11: 1613–1625.

Samabuddhi, K. 2005. Mishandling of crisis leads to serious conflict. Bangkok Post, 19 July 2005.

Sampat, P. 2000. *Deep trouble: the hidden threat of groundwater pollution*. Worldwatch Paper 154. Washington, DC, USA: Worldwatch Institute. 55p.

Savenije, H. H. G.; van der Zaag P. 2002. Water as a economic good and demand management: Paradigms and pitfalls. *Water International* 27 (1): 98–104.

Serageldin, Ismael. 1995. *Towards sustainable management of water resources*. Washington, D.C.: The World Bank, cited in http://population.wri.org/pubs_content_text.cfm?ContentID=1030

Simon, Paul. 1998. *Tapped out: the coming world water crisis and what we can do about it*. Welcome Rain Publishers, New York, NY.

SIWI. 2004. *Report on the seminar on financing water infrastructure*. Stockholm, 15 August 2004. Organized by the World Bank and the Stockholm International Water Institute.

Smets, H. 2004. The cost of meeting the Johannesburg targets for drinking water. A review of various estimates and a discussion of the feasibility of burden sharing. Revised edition. Paris: Water Academy.

Swyngedouw, E. 2003. Flows of power: The political ecology of water and urbanization. The case of Guayaquil, Ecuador (1890–1990). Paper prepared for the 3rd Conference of the IWHA, Alexandria, Egypt, December 2003.

Teerink, J. R.; Nakashima, M. 1993. *Water allocation, rights, and pricing: examples from Japan and the United States.* World Bank Technical Paper No 198, p. 68.

The Hindu. 2003. *Use Bhavani Sagar dam water for drinking purposes: HC*. Friday, Sep 26, 2003. http://www.hindu.com/2003/09/26/stories/2003092605730400.htm

Turral, H.N.; Etchells, T.; Malano, H.M.; Wijedasa, H.A.; Taylor, P.; McMahon, T.A.M.; Austin, N. 2004. Water trading at the margin: The evolution of water markets in the Murray Darling basin. *Water Resources Research* 41(7).

UNESCO (United Nations Educational Scientific and Cultural Organisation). 2003. *Water for people water for life*. World Water Assessment Program. Paris: UNESCO, Berghahn Books, Barcelona.

Winpenny, J. 1994. *Managing water as an economic resource.* Routledge, Development Policies Studies, 133 p.

Winpenny, J. T. 1997. Demand management for efficient and equitable use. In Water: Economics, management and demand. London. In Kay, M.; Franks, T.; Smith, L. 296–303. UK: E & FN Spon.

World Bank. 1993. Water resources management: A World Bank policy paper. Washington D.C.: The World Bank.

World Bank, 2003. *Water resources sector strategy*. *Strategies Directions for World Bank Engagement*. World Bank, Washington DC.

NEVADA IRRIGATION DISTRICT: MEETING THE CHALLENGES OF URBANIZATION

W. Martin Roche[1]
Gary D. King[2]

ABSTRACT

The Nevada Irrigation District (NID), located in Northeastern California and covering 287,000 acres, is facing and meeting the challenges of urbanization. NID was formed in 1921 to serve agricultural customers in Nevada and Placer Counties. NID provides treated and raw water, municipal, residential, agricultural, and industrial water to customers throughout its service area. It currently supplies over 150,000 acre-feet of water annually, and a recent study concludes that NID can meet the year 2027 predicted demand of 211,000 acre-feet per year.

Urbanization challenges include serving the City of Lincoln (Lincoln), a rapidly growing urban area that is expanding into the existing NID service area, serving municipal customers within the service area but “off the grid” of existing delivery systems, and maintaining canal right-of-ways for recreational use. NID has entered into a Memorandum of Understanding and, at the time this paper was completed, a planning agreement with Lincoln. The initial planning study has identified sites for a water treatment plant and a delivery system that would be built and operated by NID and financed by Lincoln.

Customers “off the grid”, or not near existing water treatment and delivery systems, have been unable to obtain domestic water due to the high capital cost of supplying them. NID has recently developed numerous methods to assist these areas with treated water. These methods are diverse and customized to the needs of the area. These needs include financial, site constrictions, and other needs.

At this time, NID is pursuing numerous retrofit projects that are necessary to improve reliability and capacity. One project is to replace a major canal with a pipeline to increase system capacity and reliability. NID has worked with local citizens in an effort to maintain the canal for recreational use along its right-of-way.

This paper includes a description and history of NID, and how it is meeting the above challenges of urbanization.

[1]Consulting Engineer, 13879 Naomi Way, Grass Valley, CA 95945 wmroche@usamedia.tv
[2]Chief Engineer, Nevada Irrigation District, 1036 W. Main Street, Grass Valley, CA 95945, king@nid.dst.ca.us

INTRODUCTION

History

The Nevada Irrigation District (NID), an independent special district within the State of California, was established in 1921 by a vote of the residents of Nevada County, California. At its formation it encompassed 202,000 acres. In 1926 NID was expanded to include 66,500 acres in western Placer County. During the 1920's NID obtained water rights and land to store and deliver water. In 1966 NID began hydroelectric production with the completion of the Yuba-Bear Power Project.

Description

Today NID encompasses a total of 287,000 acres (Figure 1). It supplies residential, municipal, commercial, industrial, and agricultural water, produces electricity, and public recreational areas. NID has ten reservoirs on the western slope of the Sierra-Nevada Mountains with a total storage capacity of over 280,000 acre-feet. Water is conveyed to the service areas in 400 miles of canals and 300 miles of pipeline.

Agricultural water is supplied to almost 5,900 customers who irrigate almost 26,000 acres. Over 18,000 acres of irrigated pasture is by far the major crop, followed by family gardens (4,100 acres) and golf courses and parks (1,000 acres). Wine grapes are a rapidly expanding crop. Other crops include hay, alfalfa, nurseries, apples, pears, peaches, and corn.

Water is treated at eight water treatment plants with a combined capacity of over 33 million gallons per day (mgd). Approximately 9,000 acre feet are supplied to over 18,000 municipal customers.

Recreation opportunities at NID reservoirs include camping, fishing, swimming, boating, water skiing, and sailing. NID operates parks, campgrounds, and beaches at Rollins and Scotts Flat Reservoirs, and the U. S. Forest Service operates recreation facilities at Faucherie and Jackson Meadows Reservoirs.

Seven hydroelectric power plants with a combined capacity of 86.3 megawatts produce an average of 375 million kilowatt hours of energy each year, enough to supply 60,000 homes. The electricity is sold to the Pacific Gas and Electric Company and is an important source of revenue for maintaining NID's extensive water distribution system.

Today NID has over 170 employees and an annual budget exceeding $30,000,000.

URBAN CHALLENGES

Untreated Domestic Water

In the past, up to 1,100 customers used water delivered through NID canals for domestic purposes. In 2002, the California Department of Health Services mandated NID to

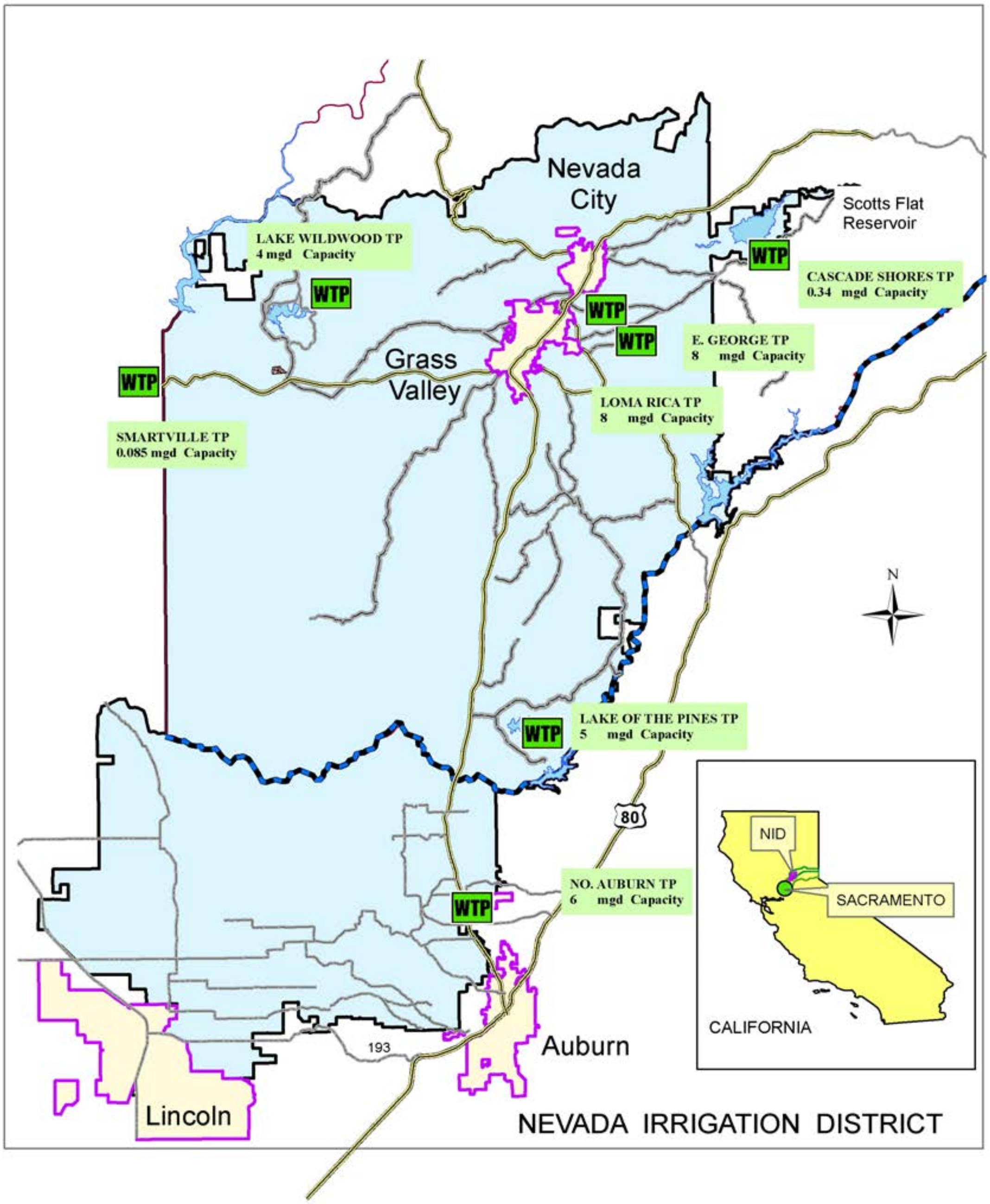


Figure 1. Nevada Irrigation District

enforce a provision of the federal Safe Drinking Water Act that prohibits use of canal water for drinking, cooking and oral hygiene. A survey found that 423 customers were still using canal water for domestic purposes. NID staff has worked with customers to enroll them in a state-approved bottled water distribution program that requires each household to purchase at least 5 gallons of bottled water per month. NID is now exploring ways to supply these customers with a more permanent domestic water supply. Many of these customers live in remote areas, far from piped treated water lines, and some live in areas where drilling adequate water wells are not possible. Grant funding opportunities for water delivery systems, discussed further in the next section, are being explored.

Small Community Domestic Water Systems

Expanding treated domestic water service to rural customers is an NID priority. Extending water lines for long distances to serve only a few customers is very expensive, and NID has had difficulty finding options to spread this cost over the entire customer base. NID is considering organizational and financial alternatives to assist customers who want to connect to domestic water lines. There are seven methods for expansion of treated water systems within NID:

Developer Projects Water mains and facilities are installed by developers, and costs are recovered through the cost of the lots, a district in which a monthly fee is charged to the home owner, or any other financing mechanism.

Variance A variance is issued when a landowner does not abut an existing water main and NID does not foresee the need for additional water mains in the area. The parcel is typically landlocked and the landowner pays the capacity and installation charges.

Temporary Service Location (TSL) A TSL is similar to a variance, however there is anticipated to be a future waterline abutting the parcel. The landowner pays capacity fees and an anticipated portion of the costs for the future waterline, and connects to the new main in the future.

District Financed Water Line Extension Program (WLE) A WLE is a short waterline extended from the end of an existing treated water pipeline, and typically involves a small group of landowners. Financing is provided by NID with the costs spread over a 20 year period at 4% interest.

The NID board of directors has approved a pilot project to extend domestic water service to seven property owners near Auburn (Figure 1). At this time there is a waiting list of similar pilot projects that are under consideration. The projects will be managed by NID.

Assessment District (AD)/Community Facilities District (CFD) AD and CFD projects involve large groups of individual lots, where the costs are high but can be spread over a large group of landowners. NID fronts the costs to develop the district, and anticipates that these costs will be recovered in the financing of the project. NID estimates the cost to provide the water service, and formation of the district is voted on by the landowners or the registered voters in the proposed district.

NID has applied for a $6.8 million loan from the California Department of Water Resources to extend service to 160 homeowners in the Cement Hill area near Nevada City (Figure 2). The loan would be repaid over 30 years by the homeowners in the CFD. The total cost of the project is estimated at $7.1 million, with NID providing the balance of the up-front cost.

Waterline Extensions During Existing Capital Improvement Projects An example of this type of project would be a treated water component combined with a planned raw water project. Some reductions in design and construction costs would be anticipated. A treated water component has been added to the Lower Cascade Canal/Banner Cascade Pipeline Project, which is described in detail in a subsequent section of this paper.

Convertible Raw Water Facility This type of project involves construction of facilities to provide raw water service in areas currently not reasonably served by treated water. The facilities are constructed to NID treated water pipeline standards, with the anticipation that treated water can be supplied in the future.

Lincoln Area Domestic Water

The City of Lincoln (Lincoln), California, located 25 miles northeast of Sacramento, is experiencing rapid growth generated by developer projects in recently annexed areas (Figure 1). It has grown from a population of 11,000 in 2000 to over 30,000 today. In 2005 it was the fastest growing city in California, growing by 23%. Historically, Lincoln has been outside of NID; however the recent growth has expanded into NID's boundary and area of water service responsibility. NID and Lincoln officials have been meeting since 1997 to develop plans to deliver treated water to this rapidly growing area. In 2004 NID entered into a water supply agreement with Lincoln and the Placer County Water Agency (PCWA). The PCWA provides water to the area of the City outside of NID, and with this agreement will supply NID treated water through existing facilities to the area of the City within NID on a temporary basis.

NID and Lincoln entered into an agreement in 2004, which called for a collaborative effort on water system planning. The planning study identified multiple sites for a water treatment plant and pipelines to bring treated water to Lincoln. NID would retain existing rights to the water; supply the water only to the area of Lincoln within NID. This project would not expand the NID boundaries.

The new treatment plant would be planned, constructed, and operated by NID and financed primarily by Lincoln. Existing Lincoln demands within NID are 1,160 acre-feet per year. The demands are estimated at 1,670 acre-feet per year in the undeveloped area within the general plan boundary, 3,400 acre-feet per year within Lincoln's existing sphere of influence, and an additional 5,560 acre-feet per year within the future sphere of influence, for a total of almost 11,800 acre-feet per year.

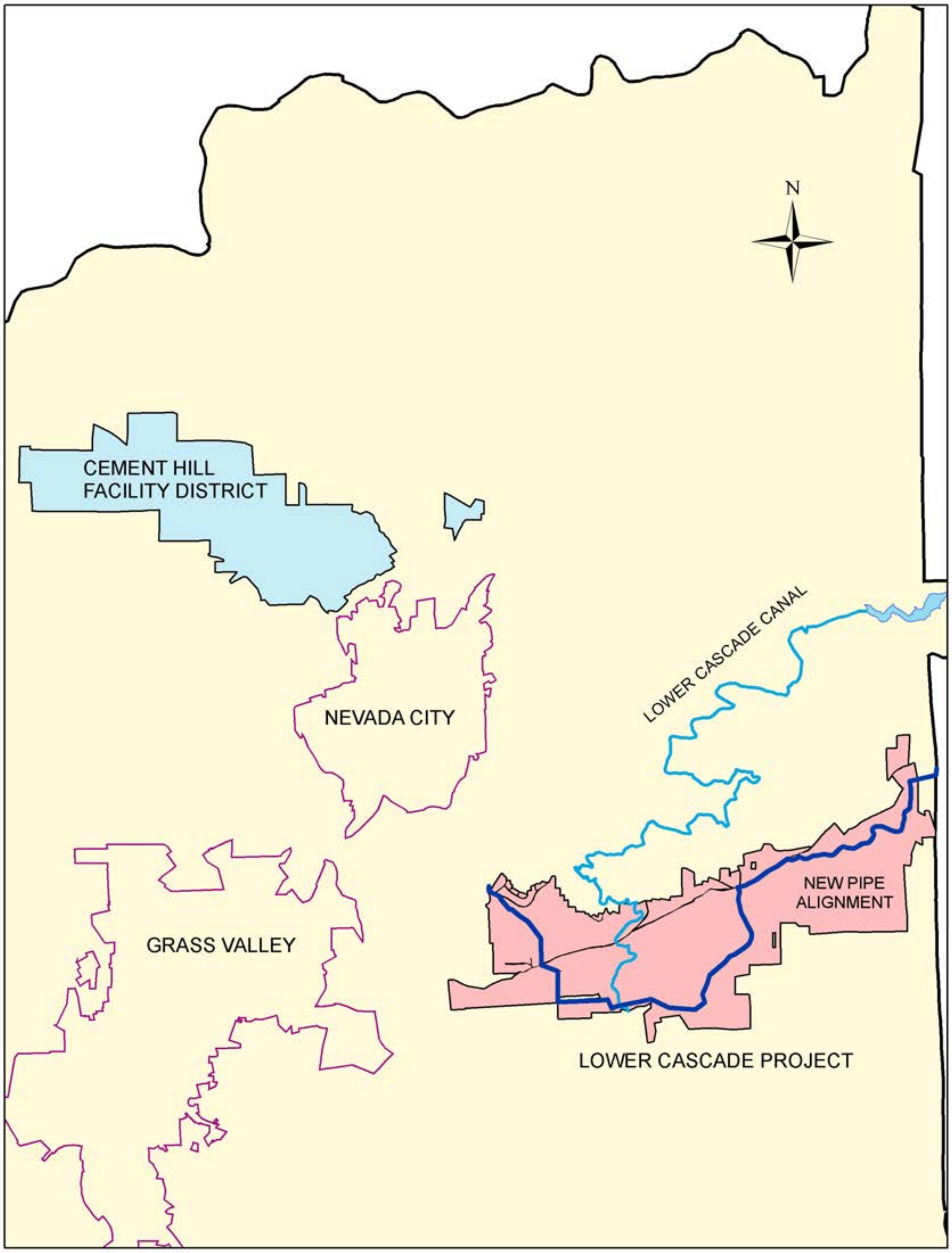


Figure 2. Banner Cascade Pipeline Project and Cement Hill Areas

Lower Cascade Canal/Banner Cascade Pipeline Project

The Lower Cascade Canal is the last remaining section of the original canal that was constructed in the mid-1800s (Figure 2). The canal needs major rehabilitation and it has inadequate capacity to meet the existing and anticipated future water demands. Its safe capacity of 40 cubic feet per second (cfs) is currently used in the summer months, and the future needs of the service area will require a capacity of 95 cfs. The canal supplies two major water treatment plants, which provide domestic water for over 25,000 residents in addition to many business and industrial users. Problems with this section of canal include; insufficient capacity, erosion of canal banks, leakage, seepage, saturated berms, property damage and prolonged outages resulting from washouts.

In 2001, NID completed Phase I of the Lower Cascade Canal Modernization Study (Study). The Study confirmed that a modernization project is needed and that a pipeline alternative would protect water quality and reduces long-term operation and maintenance costs. Phase I also included a preliminary environmental review which established methods to assess potential environmental impacts. A series of meetings with recreationists and area property owners showed that there were concerns over maintaining the characteristics of the canal system, and the proposed alignment of the pipeline.

Phase II of the Study began in 2002. Three alternative pipeline alignments were studied, as well as the fate of the existing canal. A pipeline alignment along the southern flank of Banner Mountain was studied in greater detail. Area property owners prefer an alignment that makes maximum use of existing public rights-of-way, rather than condemning private property using eminent domain.

Environmental studies conducted during Phase II were questioned by the public, and resulted in putting the entire project on hold as new studies were begun. Originally scheduled for completion in 2003, Phase II was not completed until late 2006. The NID Board of Directors approved the Banner-Cascade Pipeline Project for construction in February 2007. Construction of the Project is expected to cost $36,425,000, excluding the new power plant, more than twice the cost that was originally estimated. It is anticipated that construction will take three years.

The project consists of four major components:

A new underground raw water pipeline from the Clipper Creek siphon to the Loma Rica Reservoir and Water Treatment Plant and the E. George Water Treatment Plant. The line will consist of 21,900 feet of 48 inch pipe and 9,600 feet of 36 inch pipe and will cost an estimated $33,125,000.

A new underground treated water pipeline along portions of the raw water pipeline route. This feature was added to the project at the request of residents along the raw water pipeline route, who were concerned that a major pipeline was coming through their land, but would not supply them with drinking water. The line includes 1,800 feet of 12 inch, 12,000 feet of 10 inch, and 7,500 feet of 8 inch pipe and the cost is estimated at $2,550,000.

Reduced flows and construction of improvements in the Lower Cascade Canal and the Upper Grass Valley Canal. The canals will remain as service laterals only. Flows which now range from 15 cfs to 40 cfs would be reduced to about 2 cfs in the winter and 8 cfs in the summer. The improvements are estimated to cost $750,000. Recreational use of the canal right-of-way would be maintained.
A new hydroelectric power plant at the Loma Rica Water Treatment Plant. Preliminary studies show that as much as 1,500 kilowatts could be produced. A feasibility study needs to be conducted to further define costs and benefits.

In March 2007, a group of homeowners in the Banner Mountain area sued NID, stating that the Project's environmental report does not protect their wells or ensure that NID will supply them with water in the future. The lawsuit also says that the report does not protect property rights or the aesthetics of the neighborhood. At this time, the lawsuit has not been resolved.

Long-Term Residents at Rollins Lake Recreation Area

As with most of California, the cost of real estate has reached a point in the NID area that has made it difficult for many working people to find affordable housing. NID maintains recreation areas at two of its reservoirs that are intended for short-term camping and day use. Without NID's knowledge, the concessionaire at Rollins Reservoir issued long-term leases to 25 individuals and families to park trailers and motor homes on campsites intended for short-term recreational use. NID voided the leases and issued eviction notices to these residents, however it offered post-termination agreements to give the residents a reasonable amount of time to find alternative living arrangements.

PLANNING FOR THE FUTURE

Raw Water Master Plan

In 1985, NID developed its first Raw Water Master Plan (RWMP). Parts of the technical basis for the RWMP were updated in 1993; however a formal update of the plan was not completed. In 2003, NID began a comprehensive update of the RWMP. Phase I of the update, including the technical analyses necessary to verify existing water supply, estimate future demand, and identify constraints within the water conveyance system, was completed in 2005. Phase II of the RWMP will identify tentative plans for capital improvements needed to meet future demands. At the time of this paper, NID has finished negotiation with a consultant to proceed with these services. Phase II of the project is expected to go to the NID Board of Directors in July 2007 for approval.

Phase II of the RWMP concluded that natural runoff provides the NID system with an average of 239,000 acre-feet per year. Annual water demand is estimated at 173,300 for 2007 and is projected to increase to 211,200 acre-feet per year by 2027 (Table 1). While treated water demand is projected to increase by 71%, raw water demand (primarily for irrigation) is projected to increase by 18%. Environmental flows for instream and minimum flow requirements will remain constant.

Table 1. Current and Future Water Demands (Acre-Feet/Year)

Demand	2007	2017	2027
Treated Water	16,100	22,500	27,700
Raw Water	149,400	163,800	175,800
Environmental Flow	7,700	7,700	7,700
Total	173,200	194,000	211,200

To summarize, NID has the ability to meet current and future water demands during normal hydrologic conditions through 2027.

Phase II of the RWMP identified that in addition to the Lower Cascade Canal, 12 canal segments are running at or exceeding their design capacity, and an additional 7 canal segments will be inadequate within the next 20 years. These canal improvements are estimated to cost $16,000,000.

System Upgrades

NID has set aside funds for system upgrades that are estimated to cost over $46,000,000. In addition to the canal segments described above, two water treatment plants need to be expanded. The E. George Water Treatment Plant needs to be expanded from 10 mgd to 22 mgd at an estimated cost of $20,000,000. The Loma Rica Water Treatment Plant needs to be expanded from 8 mgd to 14 mgd at an estimated cost of $10,000,000. At the time of this paper, the E. George Plant is under design for expansion and the Loma Rica Plant site is being studied for expansion.

Strategic Planning

NID has been conducting a strategic planning process over the past two years. The process has involved NID board and staff members as well as the general public, and 21 specific goal areas have been identified and prioritized. The number one priority is the expansion of water service to areas where it is not yet available. Other top priorities include ensuring the reliability of the delivery system, preserving NID water rights, and developing a system for planning for future water needs. The strategic planning process is ongoing.

Water Alliance

NID has joined three nearby water agencies to develop a regional watershed planning program that is expected to bring state grant funds for watershed improvement projects in the region. In addition to NID, the Placer County Water Agency, the El Dorado Irrigation District, and the El Dorado Water Agency are involved. The Integrated Regional Water Management Plan will include the Cosumnes, American, Bear, and Yuba River watersheds, and will involve water suppliers and many other stakeholders. NID has proposed a pilot project for extraction of gold rush era mercury from the Bear River watershed for state grant funding. The pilot project could serve as a prototype for other mercury extraction projects throughout the area.

Power Relicensing

NID has begun the long process of obtaining a new federal license to continue the operation of the Yuba-Bear Hydroelectric Power System. A 50-year license for the project was issued in 1963 and will expire in 2013. The project was completed in 1966 at a cost of $65 million. NID has begun the initial steps in the relicensing process.

CONCLUSION

The NID, formed 86 years ago, is working hard to meet the challenges of urbanization while serving its irrigation customers and maintaining and improving its infrastructure. The challenges include; providing bottled water to customers who have been using untreated canal water for domestic supply, providing small isolated communities with treated water, meeting the need of rapidly growing Lincoln that has expanded into the NID service area, and developing the Lower Cascade Canal/Banner Cascade Pipeline Project in an area with much public interest and concern, and dealing with long-term residents at a recreational camp ground.

Planning for the future include; a Raw Water Master Plan, over $46 million in irrigation and domestic water system upgrades, initiating a Strategic Planning Process, joining nearby water agencies to form a Water Alliance to develop a regional watershed planning program, and initiating the federal power relicensing process. The next 86 years promise to be challenging and rewarding for the NID and its customers.

VARIABLE FREQUENCY DRIVE (VFD) CONSIDERATIONS FOR IRRIGATION

C. M. Burt[1]
F. Gaudi[2]
X. Piao[3]

ABSTRACT

This paper covers considerations in VFD applications, plus details a study performed by the Irrigation Training and Research Center (ITRC) to determine motor performances under varying speeds (controlled by a VFD) and loads.

Keywords: variable frequency drives, energy efficiency, motors, electricity, pumps, power usage, irrigation

INTRODUCTION

Variable frequency drive-controlled (VFD) motors have been used in many California irrigation applications to save energy (ITRC, 2002) and/or to improve control in pipelines or canals (Burt and Piao, 2002). Over the past 10 years our knowledge of proper applications and hardware has improved, and the prices of good equipment have dropped. These factors combine to make VFD applications quite appealing.

This paper presents a discussion of VFD concepts, the results of some research conducted at the Irrigation Training and Research Center (ITRC) at Cal Poly (funded by CSU/ARI and the California Energy Commission, and US Bureau of Reclamation), as well as examples of successful applications in irrigation districts.

Motor Performance at a Constant RPM (Constant Electric Frequency)

Nominal full load efficiency standards for polyphase induction motors of various sizes were specified by the US Energy Policy Act (EPAct) of 1992. Those standards apply to all motors manufactured after October 1997. Motor Decisions Matter (2003), an industry group dedicated to improving motor application efficiencies, developed Table 1 for comparison.

[1] Professor, BioResource and Agricultural Engr. Dept., and Chair, Irrigation Training and Research Center (ITRC). California Polytechnic State University (Cal Poly). San Luis Obispo, Calif. 93407-0730 cburt@calpoly.edu. 805-756-2379
[2] Irrigation Engineer, Cal Poly ITRC fgaudi@calpoly.edu
[3] Controls Engineer, Cal Poly ITRC xpiao@calpoly.edu

Table 1. Full Load Motor Efficiencies at 1800 RPM

Size (hp)	Pre-EPAct[a]	EPAct[b]	NEMA Premium[c]
1.0	76.7	82.5	85.5
3.0	81.4	87.5	89.5
5.0	83.3	87.5	89.5
7.5	85.5	89.5	91.7
10.0	85.7	89.5	91.7
15.0	86.6	91.0	92.4
20.0	88.5	91.0	93.0
25.0	89.3	92.4	93.6
30.0	89.6	92.4	93.6
40.0	90.2	93.0	94.1
50.0	91.3	93.0	94.5
60.0	91.8	93.6	95.0
75.0	91.7	94.1	95.4
100.0	92.3	94.5	95.4
125.0	92.2	94.5	95.4
150.0	93.0	95.0	95.8
200.0	93.5	95.0	96.2

a. Pre-EPAct: DOE's MotorMaster+ software version 4.00.01 (9/26/2003) "Average Standard Efficiency" motor defaults
b. EPAct: Energy Policy Act of 1992
c. NEMA Premium: NEMA MG 1-2003 Table 12-12

Motor efficiency standards for other 2, 4, 6, and 8 pole motors can be found in Douglass (2005). For comparison, EPAct efficiency standards for 20 HP motors with Open Drip Proof (ODP) enclosures are 90.2%, 91.0%, 91.0%, 90.2% for synchronous speeds of 3600, 1800, 1200, and 900 RPM, respectively.

Single speed motor (i.e., a constant RPM) efficiencies will change as the output load changes. The efficiency of a typical motor may peak at about 75% load, but it will drop rapidly below some threshold load. Figure 1 shows the approximate relationship for premium efficiency motors.

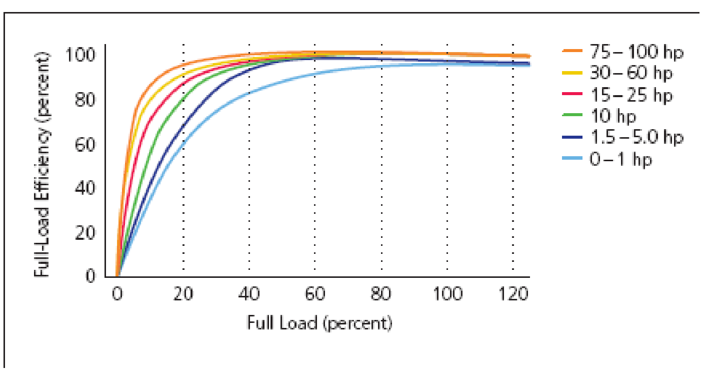


Figure 1. Induction motor efficiency as a function of load (Energy Innovators Initiative, 2003)

Wallace et al (2002) examined the efficiencies of three motors (50 HP, 100 HP, and 200 HP) from each of seven manufacturers over a range (25% to 120%) of loads – all at the rated RPM of 1800. At 25%, the efficiencies' variations (high/low) were 94.9/90.9, 94.8/90.0, and 93.7/89.6 for 200, 100, and 50 HP motors, respectively.

The power factor (PF) influences the wire sizing to the motor, and the possibility of a motor overheating. The lower the PF, the larger the current requirement for a specific load will be. The PF of a motor at a constant RPM will change as the load changes, similar to the efficiency change. Power factors listed in the Department of Energy's MotorMaster+ software (DOE 2005) vary widely among manufacturers, as did the efficiencies determined by Wallace et al (2002). However, Figure 2 provides a general illustration of how the PF varies with load for constant RPM applications.

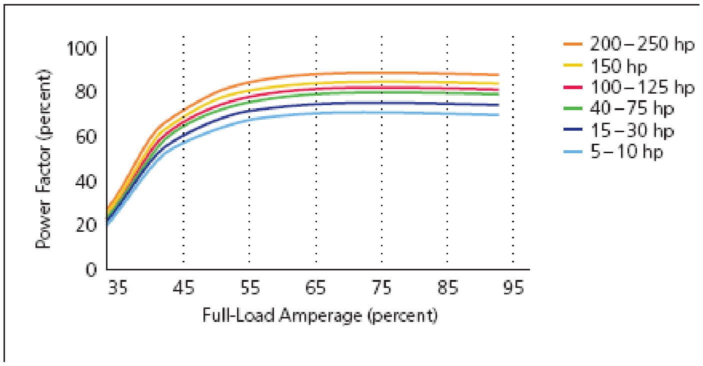


Figure 2. Induction motor power factor (PF) as a function of full-load amperage (Energy Innovators Initiative, 2003)

Variable Frequency Drive Fundamentals

As long as the frequency of the incoming power to the motor remains constant, the RPM of the motor will remain relatively constant. This is because the motor rotor turns when the moving magnetic field induces a current in the shorted conductors. The synchronous speed of the magnetic field is:

$$\text{Synchronous RPM} = \frac{F \times 120}{P}$$

where F = the frequency in Hz, and
P = the number of stator poles in any multiple of two.

For example, the synchronous speed of a four-pole motor is 1800 RPM in a 60-Hz system. Because induction motors must rotate slower than the magnetic field to produce torque, there is a slight speed difference (called "slip") between the rotor and magnetic field. The result is that the actual speed of a 4 pole motor is closer to 1750 RPM rather than 1800 RPM.

Special panels with electronic components to change the frequency from 60 Hz (in the US) to some other frequency are called "VFD controllers". They are often used to convert existing motors to variable speed applications, although with new installations the motors are generally specified as being suitable for VFD applications.

The wave forms of input to a VFD controller are sinusoidal, while the output wave forms are not. The controller output wave forms are chopped DC pulses that mimic an AC sinusoid – characteristic of a Pulse Width Modulation (PWM) VFD controller. The signal from a PWM-type VFD overlaid on a sinusoidal signal is shown in Figure 3.

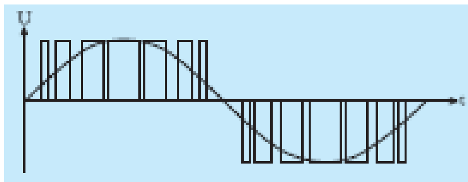


Figure 3. Pulse Width Modulation signal compared to sinusoidal. Courtesy ITT Flygt (2002)

Pump Operation with VFD Controlled Motors

There are 3 reasons to consider using a VFD controller with pumps:

1. Proper matching of the pump characteristics with the system. This first reason is poorly acknowledged in economic comparisons. Reality is such that in the field, reasonable engineers and salespersons will almost always overdesign pumps. It is very simple – if the pump is too small, there will be complaints. If, on the other hand, the pump delivers a bit more pressure than needed, there is rarely a complaint. Reasons to overdesign include:
    a. Pumps eventually have wear, and the impellers are in effect "trimmed" over time.
    b. Pumps rarely have certified performance. The pump curves are accurate within some loosely defined plus/minus accuracy. A designer must err on the side of caution.
    c. The hydraulics of the system are not precisely known. Losses through various fittings can be quite different from theoretical values, and often the as-built system includes valves, fittings, etc. of different models than what were specified. Even good designers typically add a certain pressure requirement for "miscellaneous" (a factor of safety).
    d. Source water levels change with time. River levels go up and down. Aquifer depths change from year to year, and throughout the year. There is no one "correct" lift value; the designer must design a pump for the maximum value.

2. Flow rate requirements may change with time. When the flow rate requirement for a system decreases, the operators must either bypass the extra flow, or dissipate the extra pressure developed with a lower flow rate. Both situations require more power consumption by the pump motor than what would ideally be needed. In these cases, a VFD-controlled pump can often save energy during periods of low flow.

3. Precise control of water levels or pressures requires the ability to fine-tune flow rates. VFDs provide that capability. For automatic control of canal water levels, for example, ITRC frequently uses VFD-controlled pump motors. Power savings is only a secondary concern.

Figure 4 illustrates several points about VFD control of pump motors that can be useful to know for automation projects.

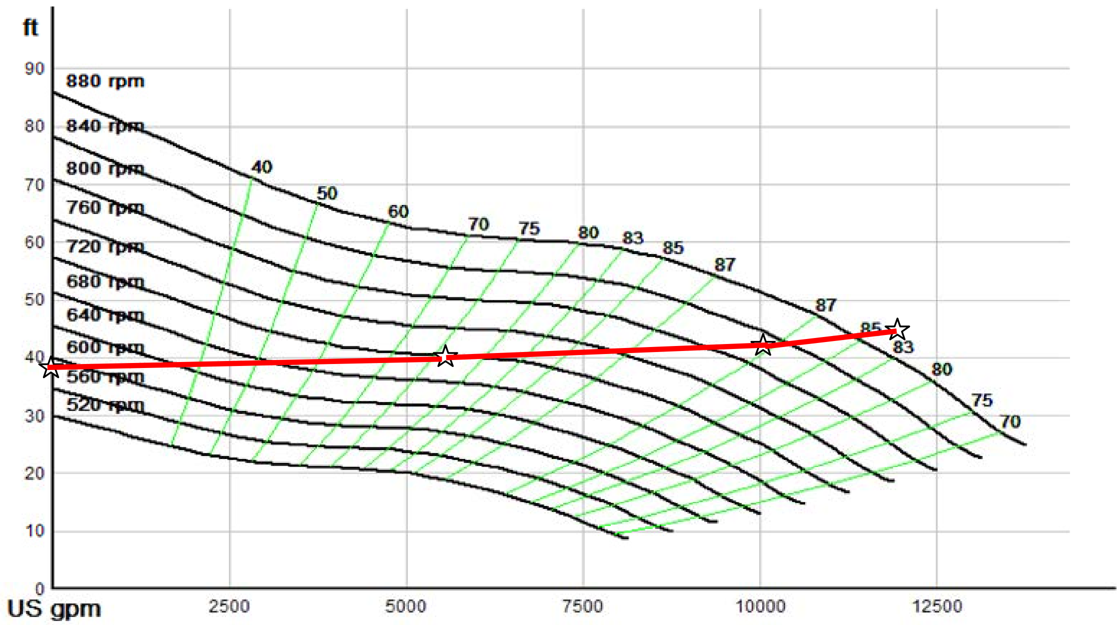


Figure 4. System curve overlain on pump curves of various RPMs. Pump curves were developed in software available from Goulds Pump (Goulds, 2003).

Points from Figure 4 include:

1. Figure 4 illustrates a common irrigation district situation in which there is a static lift from the source to the discharge. In this case, it is about 40'.
2. The RPM at zero flow rate is not zero. Rather, in this case it is about 590 RPM, which is 67% of the maximum (880 RPM) shown on the pump curves. This is important, because the fan that cools the motor should still be effective at 67% speed.
3. The change in GPM per 40 RPM change in speed is quite variable. For control, this means that the required change in pump speed to accomplish a change of flow of, say 50 GPM, is quite different depending upon what the RPM is.
4. The system curve extends past the 880 RPM curve. VFD controllers are capable of operating a motor at higher-than-nominal speed, as well as at a lower-than-nominal speed. This, of course, requires sufficient sizing of the VFD controller.

<u>Efficiency of Electrical Components with VFD Systems - General</u>.

For designers considering variable frequency drive (VFD) applications, important questions are:

1. Will the relationships seen in Figures 1 and 2 change with the introduction of the VFD?

2. Are there other losses that must be considered when computing the power requirement (quantity and quality) of a VFD installation?

A literature search indicates that when the economics of a VFD installation are computed, a variety of approaches for assuming motor efficiency have been used. The IAC (2006) computations assume a full-load motor efficiency at all speeds and loads. Rishel (2003) notes that “considering the thousands of variable-speed motors that are installed each year, it is the writer’s opinion that an independent organization such as NEMA or IEEE should develop a program for determining the estimated efficiencies of induction motors at reduced speeds and loads …”.

Wallbom-Carlson (1998) proposed an efficiency factor that includes losses from the VFD itself, losses generated in the motor by the VFD, and losses in the motor due to the motor duty-point movement. He presented an estimate of how a VFD Efficiency Factor (neglecting motor duty-point movement) would vary as a function of relative frequency. His estimate is seen in Table 2. The hypothesis was that

$$\text{Overall electrical efficiency} = (\text{VFD Factor}) \times (\text{Motor efficiency at 100\% speed at specified load})$$

Table 2. Idealized VFD Efficiency Factor (motor plus VFD controller) that ignores motor duty-point movement (Wallbom-Carlson, 1998).

% of Rated Motor Frequency	VFD Efficiency Factor
100	.97
90	.945
80	.92
70	.90
60	.875
50	.85
40	.825

Rooks and Wallace (2003) provided data from an unspecified motor manufacturer that was used with several assumptions to estimate the information shown in Table 3.

Table 3. Motor Efficiencies with VFD control (Rooks and Wallace, 2003).

Nameplate Rated HP at 60 Hz	Motor Efficiency at Various Relative Speeds (RS) and Relative Loads (RL) RS/RL		
	100/80	75/34	50/10
50	94.9	94.1	84.5
100	96.0	93.7	87.0
200	96.4	93.8	86.0

Efficiency of Electrical Components with VFD Systems – ITRC Research

ITRC conducted extensive testing of the efficiency of a VFD controller (100 HP Danfoss VLT 8000 AQUA VFD controller) with a variety of electric motors. The configuration also included a Kooltronic RP52 14,000 BTU Air Conditioner connected to the VFD aluminum enclosure. Figure 5 shows the panel arrangement. Details of the testing and results are presented in Burt et al (2007).

Figure 5. Electrical supply for the motor testing

For testing, individual motors were bolted on a machined rotating base plate (see Figure 6). The torque developed by the motor was measured (Honeywell Model IC48 150 lb range Load Cell) by sensing the tension created by a long base plate arm extension at a specific distance from the center of the motor. The load on the vertical pump shaft was created by a Denison Hydraulics goldcup series P7P closed circuit piston pump.

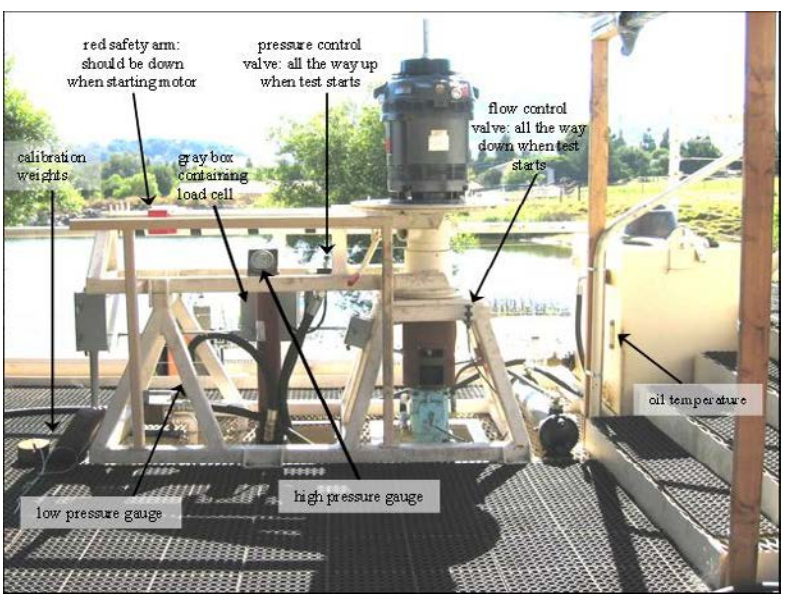


Figure 6. ITRC motor test stand.

Twelve 60 Hz, 460V ODP vertical hollowshaft motors were tested. Table 4 provides the nameplate specifications.

Table 4. Motors used in testing and their nameplate specifications.

ITRC ID	Manuf.	Nom HP	Nom. RPM	PF	EFI	Amps	Other
AO1	US	20	1765	85.6	87.5	24.3	VFD rated
A02	GE	20	1175	85	91	24.1	
AO3	US	20	1770	85.4	92.4	23.7	Premium
AO5	US	75	1780	85.3	95	87	Premium
AO6	GE	100	1780	ns	91	124	
AO9	US	40	1780	85.7	88.5	49	
AO10	GE	75	1785	85	95	87.1	
AO11	GE	50	1775	ns	ns	61.1	
AO12	US	50	1780	87.5	94.5	56	Premium
AO13	US	40	3515	89.5	90.2	46	
AO14	US	75	895	74.3	94.1	100	
AO15	GE	50	1185	ns	91.7	61.2	

Notes: ns = not stated on the nameplate
GE = General Electric
US = US Motors or Emerson

Because of the nature of the output wave form, special electronic measurement equipment was needed. A Yokogawa/GMW Danfysik Ultrastab 866R Multichannel Current Transducer System provided 6 transducers (one for each phase in and out of the VFD) with power and signal conditioning. Data from the Current Transducer System was then fed into a Yokogawa WT1600 Digital Power Meter and Communication Interface. The signals from the Yokogawa power meter were processed in a laptop computer (LT21) that was configured with LabView Real-time Module software. This processed data was then passed from laptop LT21 to a second laptop (LT11) on which National Instruments Lookout HMI/SCADA software was installed.

Power Factor. The curves in Figure 7 show how the Power Factor varies with load when a motor is operated across-the-line (ATL).

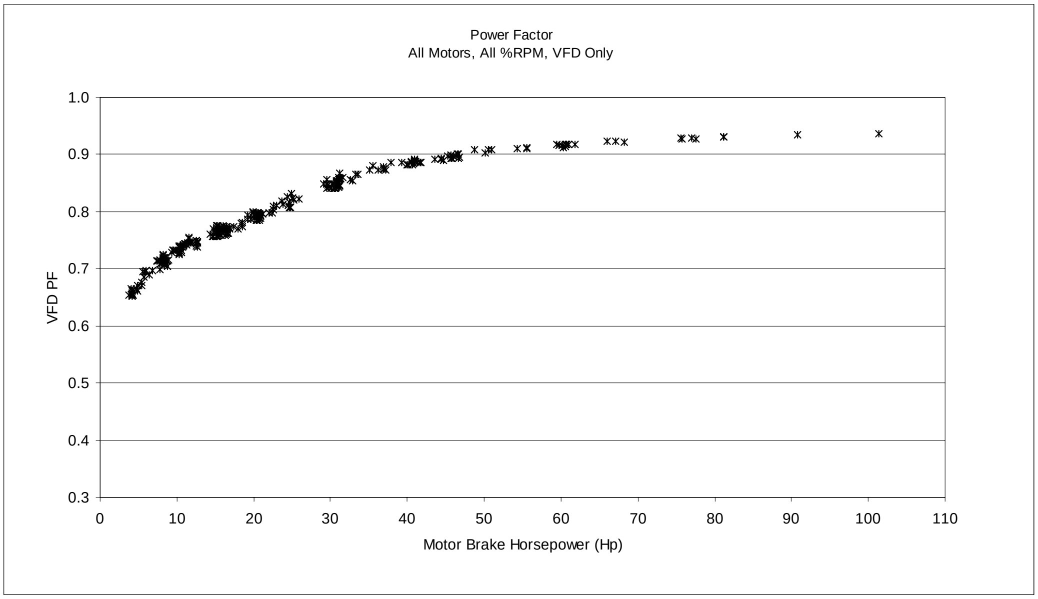


Figure 7. Power Factor versus motor output horsepower for all motors tested with Danfoss VFD controller.

VFD Controller Efficiency. The efficiency of the VFD controller itself was found to depend somewhat on the particular motor that was tested. In particular, the VFD efficiency when testing the 900 RPM (nominal) 75 HP motor averaged about 1% lower efficiency than with the 1200, 1800, and 3600 RPM (nominal) motors.

Figures 8 and 9 show VFD efficiencies at two RPMs and various Load Factors. Other efficiencies were measured at increments of 10% nominal RPM, with similar results.

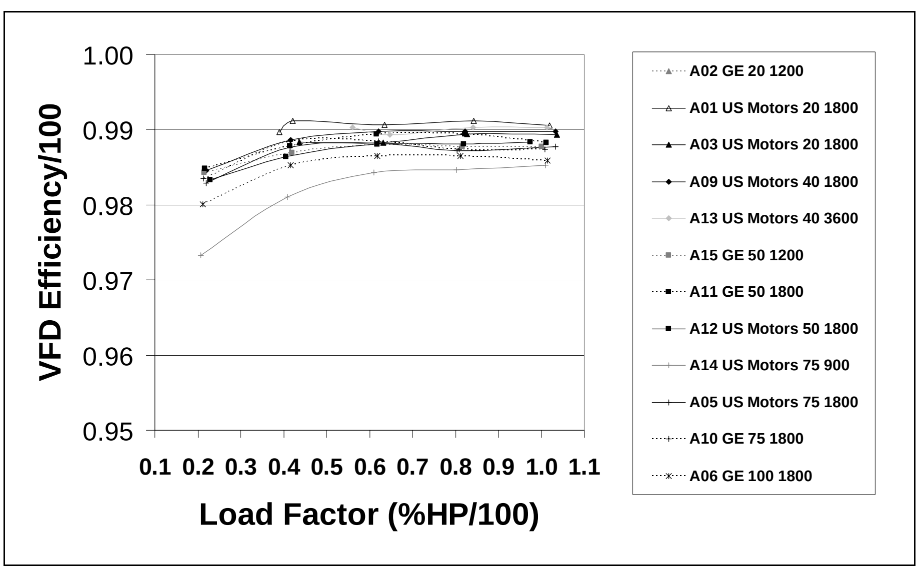


Figure 8. VFD controller efficiency with various motors at 100% RPM and varying loads.

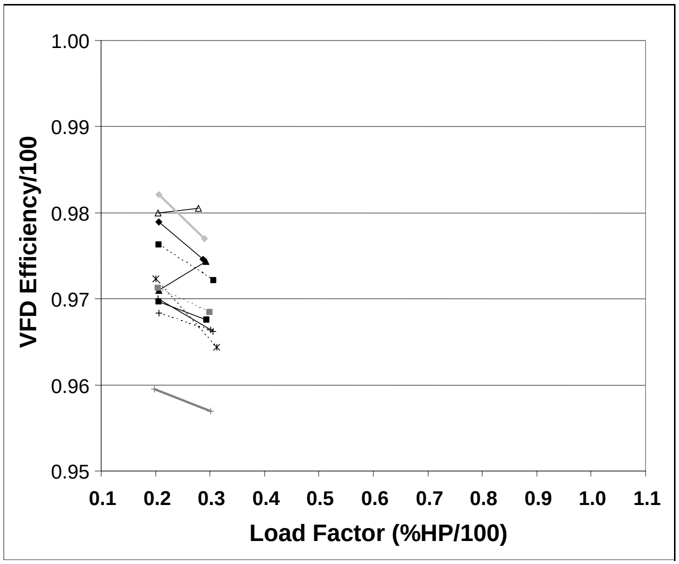


Figure 9. VFD controller efficiency with various motors at 40% RPM. Same legend as Figure 8.

Motor Efficiency. Figure 10 depicts motor efficiencies for across-the-line operation. It is clear that there are differences between individual motors. The lowest efficiency is from a 20 HP US Motors motor (A01) that is designated as a being suitable for a VFD, and the highest efficiency is from another 20 HP US Motors motor (A03) that is designated as a "Premium" motor. Four of the motors (A02, A03, A05, and A09) maintained a very high efficiency (close to 95%) across the span of relative loading.

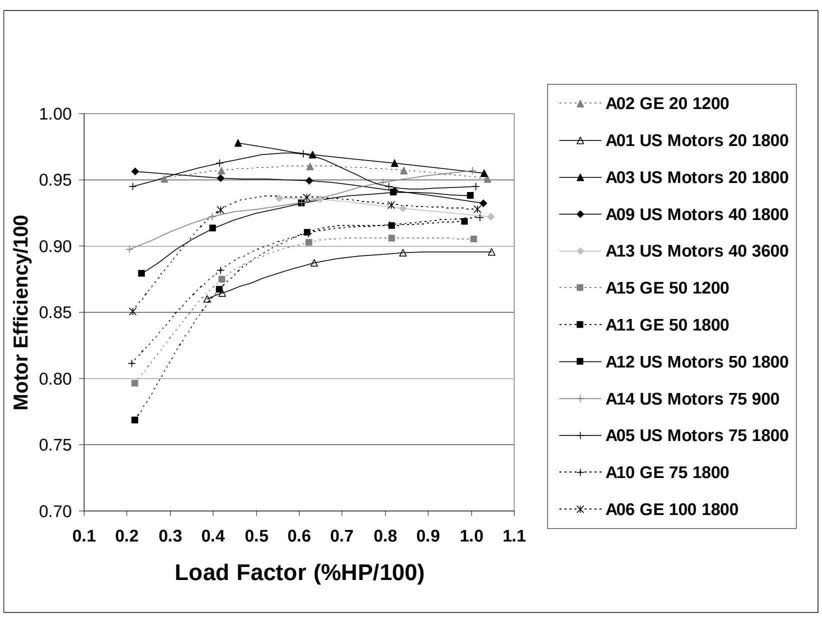


Figure 10. Efficiencies of all motors, across-the-line, at various relative loads

Figure 11 shows the performance of motors under various relative loads, at different RPMs – including a repeat of Figure 10 in the upper left hand corner for scale comparison.

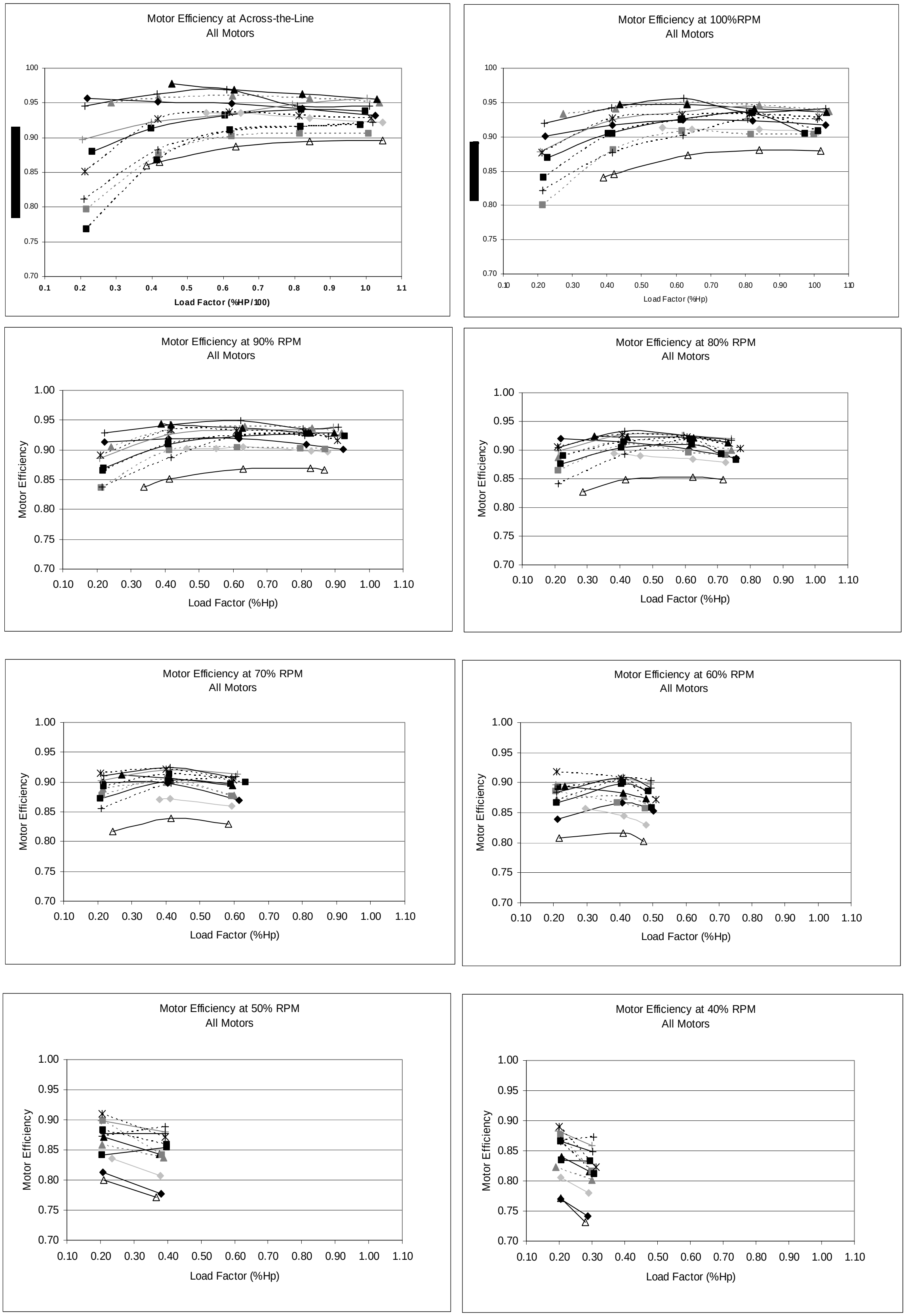


Figure 11. Motor efficiency at 10% RPM increments under various loads

Air Conditioning Power Requirement. The inefficiencies of variable frequency drive controllers are manifested as heat generation. Although the inefficiency may be small (3-5%), 3% of a 100 HP unit represents 3 HP of heat that must be dissipated. Air Conditioning units – either directly mounted to the VFD panel, or constructed to cool the entire motor control center building – are standard practice for irrigation applications. The authors suggest that if the VFD controller is 97% efficient, the additional power requirement for the AC unit can be estimated as (100% - 97%) × 2 × Input HP. For example, for a Full Load input of 110 HP to a VFD controller that operates at 97% efficiency, the additional power requirement at Full Load (assuming 50% efficiency of the AC unit) would be:

$$\text{Additional Power} = 3\% \times 2 \times 110 \text{ HP} = 6.6 \text{ HP}$$

CONCLUSIONS

1. There are a variety of reasons to use variable frequency drive controllers for pumps – only some of which involve power savings.
2. Proper application of VFD-controlled pumps in irrigation automation requires a good understanding of pump curves and hydraulic system curves.
3. Commercially available variable frequency drive (VFD) controllers are available that provide significant improvement of the Power Factor of motors, when compared to across-the-line applications.
4. The efficiency of a VFD controller appears to be slightly impacted by the motor that it is controlling.
5. The efficiencies of a motor that is operated by a VFD controller will be about the same as the efficiencies of a motor that is operated across-the-line.
6. The additional power requirement of an air conditioner for the VFD controller must be considered when determining the total power requirement for the unit and the initial and annual costs.

On the average, the relative efficiency of the electrical system with a VFD may be about 8% lower than the relative efficiency of a properly design, full-load across-the-line system. This 8% value assumes:

- No change in motor efficiency
- A 3% loss in efficiency through the VFD controller
- A parallel 5% additional power requirement for the Air Conditioner

However, it was pointed out in this paper that it is standard for pumps to be overdesigned, and for operating conditions to change over time. Therefore, one must look at much more than the electrical system efficiency to estimate power savings. It is entirely possible for a pump to deliver twice the pressure needed (and therefore consume twice the power needed), yet operate at a high mechanical and electrical efficiency. In general, anecdotal evidence and some limited data from irrigation districts show that with VFD pump applications, power consumption is reduced.

ACKNOWLEDGEMENTS

Funding for this project was provided by the California State University Agricultural Research Initiative project No. 05-3-009. Funding was also provided by the California Energy Commission Public Interest Electric Research (PIER) program, Agreement No. 400-99-014, and the US Bureau of Reclamation Grant No. 04FG210013. Donations were received from Emerson Motor Company (75, 50, and 20 HP premium efficiency motors), Thoma Electric of San Luis Obispo (technical assistance for the electrical installation), and Pacific Gas and Electric Co. (pressure gauges), and Branom Instrument Co. of Sacramento (Danfoss VFD controller).

REFERENCES

Burt, C.M., X Piao, F. Gaudi, B. Busch, and NFN Taufik. 2007. Electric Motor Efficiency Under Variable Frequencies and Loads. Irrigation and Drainage Journal of ASCE. Accepted for publication Jan 2007.

Burt, C.M., D.J. Howes, and G. Wilson. 2003. California Agricultural Water Electrical Energy Requirements. ITRC Report No. R 03-006. Prepared for the Public Interest Electric Research program of the California Energy Commission. Irrigation Training and Research Center. California Polytechnic State University. San Luis Obispo, CA. 154 pages. http://www.itrc.org/reports/energyreq/energyreq.pdf

Burt, C.M. and X. Piao. 2002. Advances in PLC-Based Canal Automation. Proceedings of United States Committee on Irrigation and Drainage Conference on Energy, Climate Environment and Water — Issues and Opportunities for Irrigation and Drainage. Held in San Luis Obispo, CA. July 9-12. pp. 409-422.

DOE. Department of Energy. 2005. MotorMaster+ (Version 4) software. http://www1.eere.energy.gov/industry/bestpractices/software.html#mm

Douglass, J. 2005 (updated). Induction Motor Efficiency Standards. Washington State University Extension Energy Program. WSUEEP02_029. 8 pages.

Energy Innovators Iniative. 2003. Technical Fact Sheet – Premium-Efficiency Motors. Cat. No. M144-21/2003E; ISBN 0-662-35668-3. Office of Energy Efficiency. Natural Resources Canada. Ottawa, ON. Canada.

Goulds. 2003. Turbine Pump Selection, Version 7.1 Developed for Goulds Pump Turbine (ITT Industries) by Engineered Software, Inc. Lacey, WA 98503-5941

IAC. 2006. Electric Motor Systems. Industrial Assessment Center. Center for Energy Efficiency and Renewable Energy. Univ. of Mass., Amherst. http://www.ceere.org/iac/assessment%20tool/ARC2410.html#efftable

ITRC. 2002. Variable Frequency Drives and SCADA – Are They Worthwhile Investments? ITRC Report No. R 02-006. Irrigation Training and Research Center. California Polytechnic State University. San Luis Obispo, CA. 10 pages. http://www.itrc.org/reports/vfd/vfdandscada.pdf

Motor Decisions Matter. 2003. Efficiency Values. www.motorsmatter.org

Nailan, R.L. 2002. Just How Important is Drive Motor Efficiency? Electrical Apparatus. Barker Publications, Inc. Chicago, IL. March issue.

Rishel, J.B. 2003. How to Calculate Motor Efficiency for Variable Speed Centrifugal Pumps. Engineered Systems. August issue.

Wallace, A.K., J. A. Rooks, and J. R. Holmquist. 2002. Comparison Testing of IEEE Standard 841 Motors. IEEE Transaction on Industry Applications 38(3):763-768.

Wallbom-Carlson, A. 1998. Energy Comparison. VFD vs. On-Off Controlled Pumping Stations. Scientific Impeller (ITT Flygt AB, Sweden). Pg. 29-32.

ACCURACY OF RADAR WATER LEVEL MEASUREMENTS

Janice M. Fulford[1]
Lee W. Ester[2]
John W. Heaton[3]

ABSTRACT

Radar water-level sensors are generating a lot of interest among hydrographers because of their ease of installation and low maintenance. However, limited information is available on the accuracy and performance of radar sensors in the field. This paper presents test results from recent field measurements made with radar water-level sensors. Field data collected with two pulse radars, (Design Analysis Associates H-3611 and the Ohmart Vega Puls 62) and one continuous wave frequency modulated radar (Saab Rosemount) during lake drawdown at Horse Mesa Dam, Arizona, are presented and compared against a conventional float-well system. (The use of firm, trade and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Government). Measured radar data were analyzed for possible sources of systematic measurement uncertainty (error) including sensor height above water (air gap), air temperature and surface waves.

The Ohmart Vega sensor has a systematic uncertainty from varying air gap. The H-3611 and the Saab Rosemount sensor do not have an obvious systematic uncertainty from varying air gap. None of the radar sensors have an obvious uncertainty from surface waves when compared with the float-well systems. No systematic uncertainty due to temperature or wind speed was noted for any of the radars. Analysis of the field data indicate that the data measured by the H-3611 and the Saab Rosemount are not statistically different from that collected by the float-well system. For the data measured by the Ohmart Vega, a systematic error of about 0.3 ft over a 35-ft change in water level occurred during the field measurements.

INTRODUCTION

Water-level measurements are used by water managers and hydrographers to compute water flow and volumes. The accuracy and performance of stage instrumentation directly affects the quality of these parameters. Instrumentation systems commonly used to measure water level are: (1) a float with shaft encoder in a stilling well (float-well), (2) non-submersible pressure-transducer bubbler systems, (3) submersible pressure transducer systems and (4) acoustic systems.

Traditionally, the U.S. Geological Survey has used float-well and pressure sensor systems and the Salt River Project (SRP) has used float-well systems to measure water level. Acoustic systems have not been routinely used because the accuracy of open-air acoustic systems, which are affected by air temperature gradients, does not meet the requirements of the U.S. Geological

[1] Hydrologist, U.S. Geological Survey, Building 2101, Stennis Space Center, MS 39529
[2] Measurement Services Manager, Salt River Project, Tempe, AZ
[3] Hydrologist, U.S. Geological Survey, Tempe, AZ, 85281

Survey and the SRP. Unfortunately, the other systems have orifices in the water that are subject to fouling and damage by debris, sediment and biota. These systems are also costly to install and maintain. Float-well systems require the construction of a stilling well and pressure systems require trenching to bury cables or pressure lines. Maintenance of the orifices can require labor-intensive flushing or clearance of the orifices. Additionally, float-well systems have long tapes and floats that can become tangled or damaged and can be difficult to replace.

Both the U.S. Geological Survey and the SRP are studying radar sensor technology in an effort to reduce installation and maintenance costs of water-level measurement systems. Radar sensors do not need to have contact with the water to measure the water level and do not require the construction of stilling wells or orifice lines. Moreover, because radar is a "non-contact" measurement method, it is not susceptible to having a submerged orifice obstructed, silting of a stilling well or damage by sediment or floating debris. Floating debris or objects in the “line of sight” of the radar may adversely affect water-level measurements. Typically, water-level radars are installed on a stable platform, such as an existing bridge, that positions the radar antenna over the water.

This paper presents test results from recent field measurements made with three different radar water-level sensors. The field data were collected in collaboration between the SRP and the U.S. Geological Survey, Hydrological Instrumentation Facility and the U.S. Geological Survey, Tempe, Arizona office. Data collected by the Design Analysis Associates H-3611, Ohmart Vega Puls 62 and a Saab Rosemount radar during lake drawdown at SRP Horse Mesa Dam, Arizona, are presented and compared against float-well measurements. (The use of firm, trade and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Government).

WATER-LEVEL RADAR SENSORS

A radar sensor measures water level by propagating electromagnetic energy with an antenna. Because radar energy reflects and scatters similarly to light, objects in the propagation path reradiate the microwave energy back to the radar antenna. The time it takes for the energy to return to the radar (travel time) is determined with the radar’s integral digital signal processing software. The resulting travel time is used to determine the distance to the object (or water level).

Radar energy spreads with distance like a flashlight beam. Unlike acoustic water-level sensors, the propagation of radar energy is not significantly affected by air temperature or by moderate rainfall (Serafin, 1990). Unfortunately, radar sensors cannot be used to measure water levels thru ice cover, because radar energy does not reliably penetrate ice. Because any object in the “line of sight” of the radar propagation path (or beam path) will reflect energy, an unobstructed path is needed between the antenna and the water surface. Radar sensors must be placed directly over the water surface so that the reradiated energy reflects directly back to the radar antenna. This makes radar sensors ideal for installing on rigid bridges or vertical structures next to water.

Radar systems for water-level measurements were originally designed for industrial tank measurement and adapted for use in open air. The frequencies used for tank radar systems typically range from 10 to 24 gigahertz (GHz). Tank radars are either continuous wave frequency modulated radars or pulse radars. Because industrial tank radars are used in enclosed structures, not all tank radars are licensed for open air use. Using radar systems in the open air require the radar unit to be licensed by the Federal Communications Commission (FCC) to ensure that the system does not interfere with other transmissions or pose a health hazard. Some radar systems' frequencies and bandwidths may need site specific FCC licensing for use. Some of the features added to radars used for open air water-level measurements include SDI-12 communications and battery power.

PREVIOUS STUDIES OF WATER-LEVEL RADAR SENSORS

A simple uncertainty analysis of water-level sensors (Fulford and Davies, 2005b) found that radar systems with an accuracy of 0.026 ft are more accurate than uncorrected pressure systems, except at low stages. However, float-well systems were found to have the best accuracy throughout a large range (30 ft) of water levels. Best measurement accuracy is typically required at low stages. In contrast, radar accuracy typically improves with decreasing distance to water (increasing stage).

Previous U.S. Geological Survey laboratory and field testing (Fulford and Davies, 2005a) of a Design Analysis Associates H-360 continuous wave frequency modulated radar found a measurement accuracy of about 0.03 ft and a systematic measurement uncertainty due to air temperature. Data collected by the H-360 had lower minimum water levels than either float-well system or pressure sensors. This was attributed to the wave troughs focusing the radar energy back at the radar antenna and the wave crests dispersing the energy away from the antenna, resulting in a fictitiously lower water surface. Additionally, frequency analysis of radar measurements at two field sites showed the radar data adversely affected by sampling at a 15-minute interval. The radar in this study was turned on for 2 minutes to measure the water level and then turned off until the next measurement was collected, 15 minutes later. The 15-minute sampling interval is traditionally used by the U.S. Geological Survey for water-level measurements. The 2 minutes of measurement by the radar did not allow the higher frequency wind-driven surface waves to be filtered out by the radar sensor's signal processing firmware. This resulted in the radar measurements having an uncertainty due to wind-driven surface waves that was not found in either the float-well or pressure sensor systems measurements.

WATER-LEVEL RADAR SENSORS STUDIED

The three radars used to collect the data presented in this report are: Design Analysis Associates (DAA) H-3611, Ohmart Vega Puls 62 and a Saab Rosemount Tank Radar (figure 1). The DAA H-3611 and Ohmart Vega Puls 62 are pulse radars that use a 26 GHz frequency and have FCC approval for open air use. These units have a similar size, about 18 inches long by about 4 inches in diameter. Both of these models are 12 volt battery powered and use SDI-12 and RS232 communications. Power consumption of the units is less than 12 mA. This allows the units to continuously measure the location of the water surface and filter out the effects of small waves

Figure 1. Pictured from left to right, Design Analysis Associates H-3611, Ohmart Vega Puls 62 and Saab Rosemount Tank Radar. Photos are not to scale.

and use battery power. They have an air gap range from 0.17 ft to 72 ft and weigh about 6 lbs. Any SDI-12 compatible data logger can be used to record the measurements. The Saab Rosemount radar is a continuous wave, frequency modulated radar that uses a 10 GHz frequency. It uses line power and is about 30 by 17 inches and weighs 55 lbs. It has a measurement range of at least 130 ft. Similar to the other radar units, the Saab Rosemount continuously measures the location of the water surface and filters out the effects of small waves.

FIELD MEASUREMENTS

Field data were collected at 15-minute intervals during the drawdown of the lake at Horse Mesa Dam. Water-level data were collected from the Saab Rosemount radar and a SRP shaft encoder attached to the float and logged by SRP's Lake Level SCADA system. Water-level data were collected from the DAA H-3611 and Ohmart Vega radars and from an additional shaft encoder attached to the SRP float-well system and logged to a U.S. Geological Survey logger. Hourly weather data from a Vaisala WTX 510 and digital camera images taken every 3 hours were recorded to the U.S. Geological Survey logger. Figure 2 shows the installation at the Horse Mesa Dam and was taken by the digital camera attached to the logger. Data from the SRP logger covered the period from October 1, 2006, thru November 2, 2006. Data from the U.S. Geological Survey logger covered the period from September 13, 2006, thru November 3, 2006. No adjustments to the sensors were made during the measurement period. No floating debris occurred during the measurement period.

Comparison of Radar and Float-Well Data

Comparison of simple statistics: average, standard deviation, minimum and maximum, computed for the collected water-level measurements can indicate whether the radar measurements are as accurate as the float-well system. Because the resolution of the float-well system water-level measurements is 0.01 ft, statistical differences that are less than or equal to 0.01 ft are not significant. Summary statistics for the data collected by the U.S. Geological Survey logger from September 13, 2006, thru November 3, 2006 are listed in table 1. The measurement period spans about 51 days and 4874 measurements for each sensor. The water level changed about 35 ft during the period. Few obvious outliers were detected in the data. An obvious outlier measurement on September 24 at 3:15 for the DAA H-3611 and Ohmart Vega radars was removed from the data prior to the statistical analysis. The Ohmart Vega radar had an additional outlier measurement on October 5 at 14:00 that was also removed. Birds or other objects temporarily in the line of sight and radio interference sources such as radios, electric motors and power lines could cause outliers in the radar data.

The DAA H-3611 statistics have excellent agreement with the float-well system. The average, standard deviation and maximum values for the DAA H-3611 are within 0.01 ft of the values for the float-well system. The minimum water level is slightly lower than the float well, by -0.04 ft.

Figure 2. Photo of installed radars and stilling well at Horse Mesa Dam, Arizona, by digital camera attached to logger.

Table 1. Summary statistics for water-level data logged from September 13, 2006, 13:30 to November 3, 2006, 8:00 at 15-minute intervals (4874 measurements) during lake drawdown at Horse Mesa Dam, Arizona.
[[1]data from U.S. Geological Survey encoder attached to float-well system; ft, feet]

	Float-well[1]	DAA H-3611	Ohmart Vega Puls 62
Average (ft)	32.32	32.31	32.52
Standard deviation (ft)	9.91	9.92	9.82
Minimum (ft)	17.33	17.29	17.61
Maximum (ft)	52.39	52.39	52.39

Table 2. Summary statistics for water-level data logged from October 1, 2006, 0:00 to November 2, 2006, 4:30 at 15-minute intervals (3090 measurements) during lake drawdown at Horse Mesa Dam, Arizona [ft, feet].

	Float-well	Saab-Rosemount	DAA H-3611	Ohmart Vega Puls 62
Average (ft)	26.44	26.44	26.43	26.70
Standard deviation (ft)	4.70	4.69	4.69	4.65
Minimum (ft)	17.54	17.50	17.46	17.81
Maximum (ft)	35.56	35.57	35.56	35.75

The Ohmart Vega statistics are slightly different from the float well system, +0.20 ft for the average and + 0.09 ft for the standard deviation. The minimum water level is +0.28 ft higher than the float-well system.

Summary statistics for the data collected by the SRP Lake Level SCADA system from October 1, 2006, thru November 2, 2006, are listed in table 2 with statistics for the data collected by the U.S. Geological Survey logger over the same period. The statistics are for 3090 measurements over approximately 32 days. The water level changed about 19 ft during the period.

The Saab Rosemount statistics have excellent agreement with the float-well system. The average, standard deviation and maximum values for the Saab Rosemount are within 0.01 ft of the float-well system. The minimum water level is slightly lower than the float well, -0.04 ft. During this measurement period, the DAA H-3611 statistics have excellent agreement with the float-well system except for the minimum water level, which is slightly lower than the float well, -0.08 ft. The Ohmart Vega radar statistics are slightly different from the float-well system,+ 0.26 ft for the average and -0.05 for the standard deviation. The minimum water level is +0.27 ft higher than the float-well system.

Effects of Air Temperature, Wind Speed and Air Gap

Differences between the radar measurements and the float-well were examined using plots with air temperature, maximum wind speed and air gap distance. No obvious influence of air temperature or wind speed on the differences was noted for any of the radars. These plots are not included in the report. Figures 3 and 4 show plots of differences between the float-well measurement and the radar measurement plotted against increasing air gap. During the drawdown period the air gap ranged from about 17 ft to 53 ft.

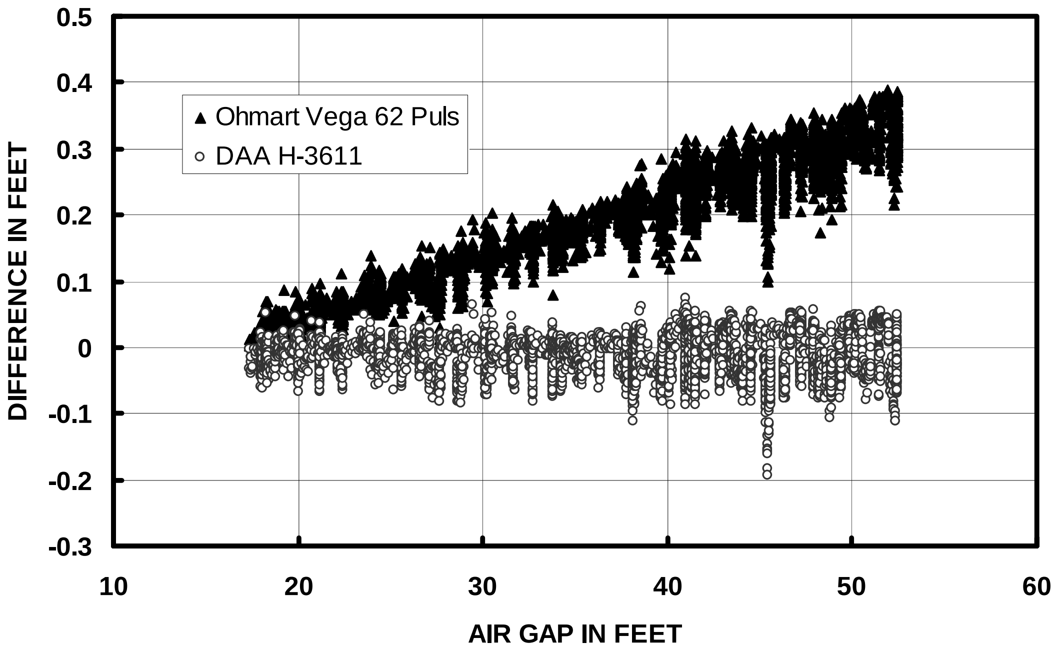


Figure 3. Difference between radar and float-well system plotted by air gap.

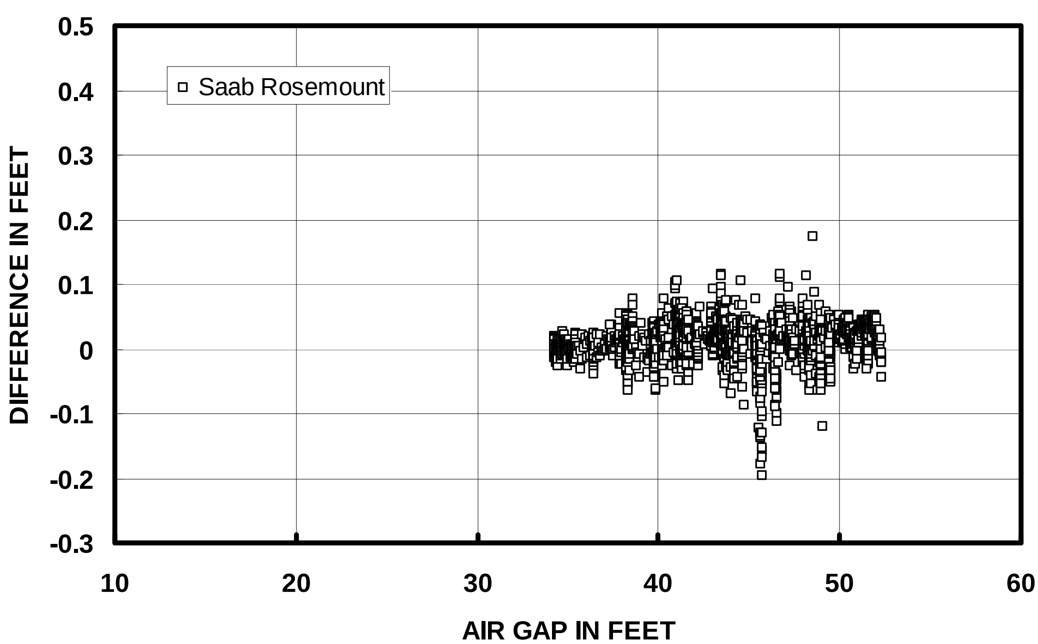


Figure 4. Difference between Saab Rosemount radar and float-well system plotted by air gap.

The DAA H-3611 and the Saab Rosemount radar have no obvious trend with air gap. A linear regression of the differences with air gap yielded very low correlation coefficients of 0.001 (DAA H-3611) and 0.016 (Saab Rosemount). The Ohmart Vega radar differences have a linear trend with air gap (figure 3). A linear regression of the differences with air gap yielded a 0.009-ft difference per foot of air gap and a correlation coefficient of 0.847.

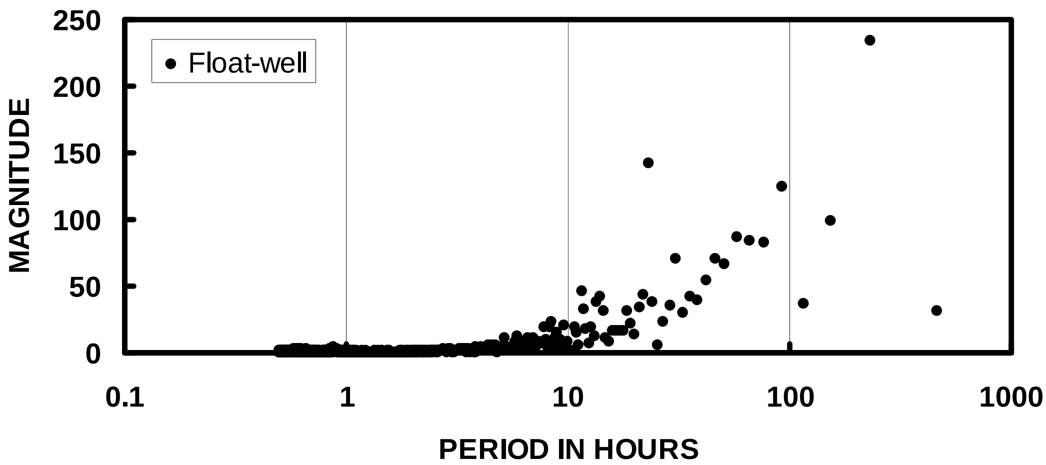
The Ohmart Vega systematic difference with the float-well system measurements may be due to a small clock error that prevents accurate timing of the radar pulse travel time. This could also explain the slight differences with the float-well system statistics. The effects of clock error on low stage measurements potentially could be reduced by zeroing (or calibrating) the radar to a reference measurement at a low stage. Measurement error due to clock error would then be larger for the higher stages. The slightly lower minimum water levels measured by the Saab Rosemount and DAA H-3611 may be due to a bias from surface-wave troughs preferentially reflecting energy back to the radar antenna. Controlled laboratory experiments on the effects of wave action on measurement bias might help quantify how significant this effect is and perhaps suggest how to minimize the adverse effects.

Response to Surface Waves

Frequency analysis was used to supplement the simple statistical analysis and to help find the difference between float-well and radar responses to surface waves. The field data for the radars and the float-well system were transformed into frequency data using fast Fourier transform techniques (Bracewell, 2000). Fourier transforms convert time-series data into the frequency domain. The trend and mean in the measured water levels due to the lake drawdown were removed from the measured data prior to the Fourier transform of the data. Fourier analysis requires that the data have no trends and a mean of zero. Because of the effort required to de-trend the data only a subset of the data that varied linearly was transformed. For the float well, DAA H-3611 and the Ohmart Vega, the selected length of record transformed was from September 15 at 15:45 to October 4 at 20:00, about 19.2 days. For the Saab Rosemount the period transformed was from October 14 at 21:30 to October 29 at 17:30, about 14.8 days. For comparison with the Saab Rosemount, the same period was also transformed for the float-well system.

Only the magnitude of the transform data is plotted in figures 5 and 6 as a function of period in hours. A period is the time from crest to crest of a wave and is the inverse of frequency. Because of the sampling interval of 15 minutes, the shortest periodic signal that can be detected from the transformed data is 0.5 hour. The longest periodic signal that can be detected is half the length of the record transformed. For the 19.2-day record length, the longest periodic signal that can be detected is 460.75 hours. For the 15-day record length, the longest periodic signal that can be detected is 356.0 hours.

The magnitude indicates how much energy is present for a water wave of a particular period. A low magnitude indicates little or no waves present at that period. For river systems, most of the energy is at the larger wavelengths with periods of several hours, reflecting hours and days that it



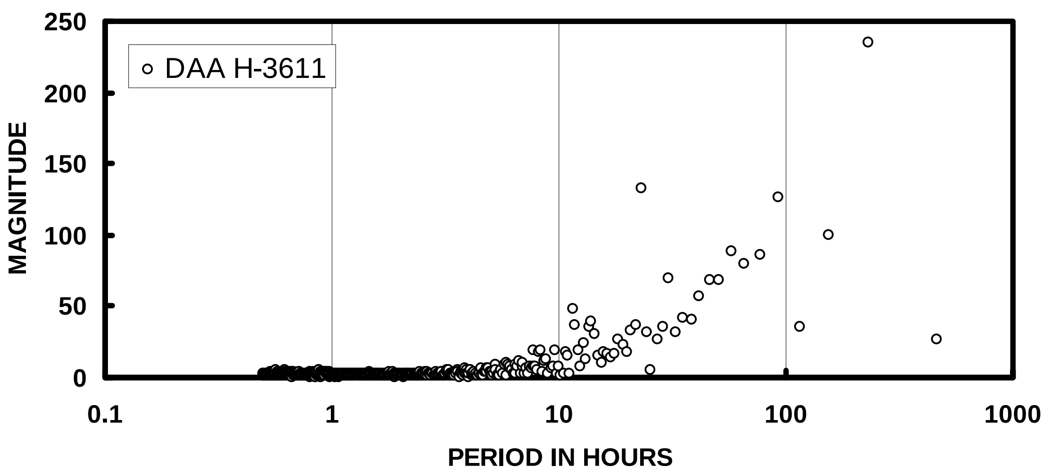
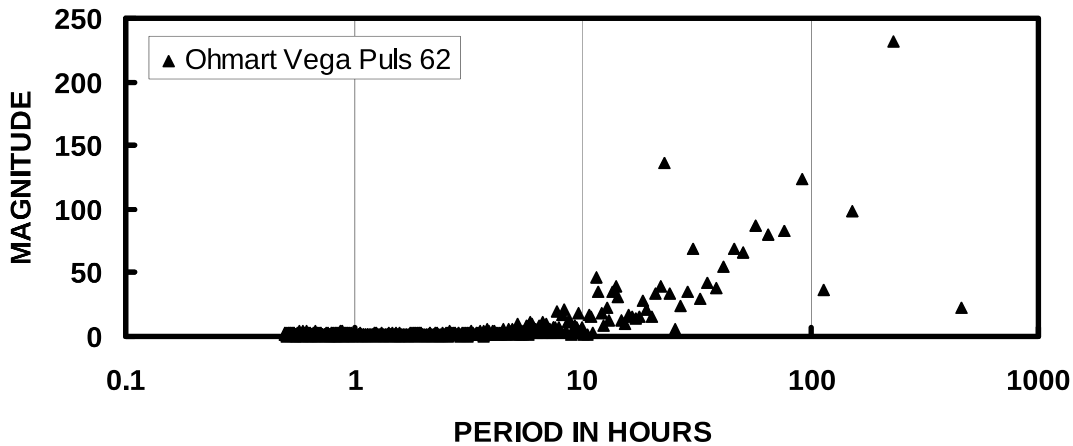


Figure 5. Plots of Fourier amplitudes of water-level data measured by a float-well system and a DAA H-3611 from September 15 at 15:45 to October 4 at 20:00 during drawdown of lake at Horse Mesa Dam.

takes for rainfall events to cause the water level in rivers to rise and fall. Wind, however, can produce water waves with periods of 5 minutes or less (Kinsman, 1965). For float-well systems, the stilling well acts to damp out (or filter) the small surface waves that are produced by wind or other small flow disturbances. The resulting water level is closer to the local (in time) average water level and is the measurement that is traditionally used to compute flow.

The transformed data for all radars, DAA H-3611, Ohmart Vega and Saab Rosemount, have excellent agreement with the transformed data for the float-well system. The plots in figure 5 and figure 6 look identical, indicating that the radars filter out the small surface waves similar to the float-well system. The plots also show that the radar systems response to all periodic changes in water level in the data collected are the same as those for the float-well system. The



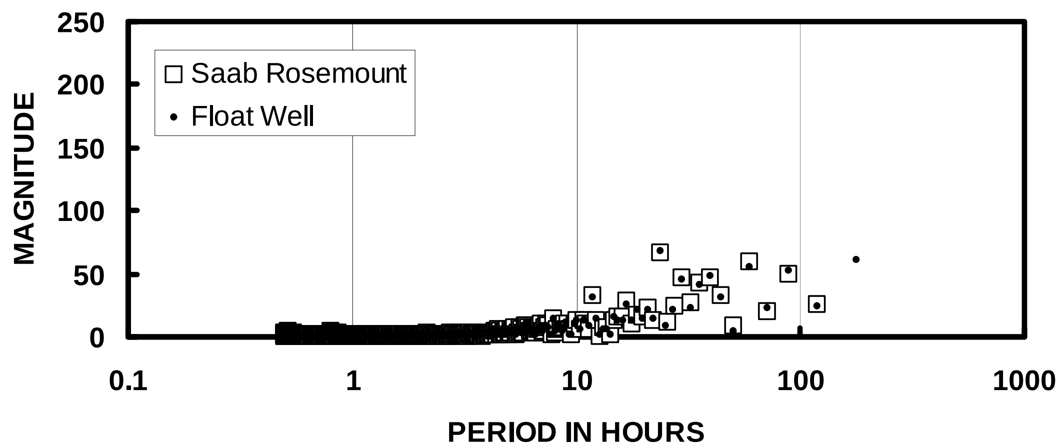


Figure 6. Plots of Fourier amplitudes of water-level data measured by a Ohmart Vega Puls 62 and a Saab Rosemount and float-well system from October 14 at 21:30 to October 29 at 17:30 during drawdown of lake at Horse Mesa Dam.

plot in figure 6 for the Saab Rosemount includes data for the float-well system over the same period. The plot does not have data at the longer periods because the length of record was shorter and the data are for a slightly different period.

SUMMARY

Radar instruments may provide significant advantages over traditional water-level sensors. They require less effort to install than either float-well systems or pressure sensor systems. Radar sensors require less maintenance than traditional water-level sensors because they are not in contact with the water. Field measurements at the Horse Mesa Dam demonstrate that radar water-level measurements can have similar accuracy as float-well systems over a change in stage of 35 ft and air gaps up to 53 ft.

The DAA H3611 and the Saab Rosemount both have measurement statistics and frequency responses that are not distinguishable from the statistics and frequency response of the float-well system. The only exception is the minimum water level measured, which is lower by -0.04 to -0.08 ft than the minimum measured by the float-well system. The lower minimums may be due to wave troughs preferentially reflecting energy back to the radar antenna, resulting in a fictitiously, slightly lower water surface. The Saab Rosemount and the DAA H3611 do not have an obvious correlation between air gap and measurement accuracy. The other radar sensor used, Ohmart Vega Puls 62, has slightly different statistics and a similar frequency response to the float-well system over the measurement period. The statistics were different by +0.20 ft for the average and +0.09 ft for the standard deviation over 51 days. The minimum water level is +0.28 ft higher than the float-well system. The slightly different statistics may be due to a small error in timing the radar pulse travel time which resulted in increasing error with increasing air gap.

All of the radars used to collect the data presented in this report continuously measure the location of the water surface and filter out the effects of small waves. This resulted in the radars having a frequency response to water-level changes that is very similar to the float-well system. Radar water-level sensors are an exciting new tool for measuring water levels. The drawbacks of radar sensors are the inability to measure water-level under ice cover or floating debris, the need to have a clear “line of sight”, a small low measurement bias that is likely a function of surface waves, and the need to position the radar antenna directly over the water surface. The data collected during lake drawdown at Horse Mesa shows that there are commercially available radar systems capable of replacing the traditional water-level sensors.

REFERENCES

Bracewell, Ronald N. 2000, The Fourier transformation and its applications: Boston, Mass. McGraw Hill Co., 144 p.

Fulford, Janice M. and Davies, William J. 2005a, March “Radar Water-Level Measurement for Open Channels”, in Proceedings of Third International Conference on Irrigation and Drainage (USCID), San Diego, CA.

Fulford, Janice M. and Davies, William J. 2005b, May “Radar Stage Uncertainty”, in Proceedings of EWRI/ASCE 2005 Conference, Anchorage, AK.

Kinsman, Blair, 1965, Wind Waves: Englewood Cliffs, NJ., Prentice Hall, 676 p.

Serafin, Robert J, 1990, Meteorological Radar, in Radar Handbook, Editor M. Sholnik, Boston MA, McGraw Hill, 23.7-23.8p.

TRANSITION SUBMERGENCE AND HYSTERESIS EFFECTS IN THREE-FOOT CUTTHROAT FLUMES

Alfonso F. Torres[1]
Gary P. Merkley[2]

ABSTRACT

New and detailed hydraulic laboratory measurements for a 3-foot Cutthroat flume with four different throat widths were collected and analyzed. It was found that there is no definitely observable transition submergence at which the regime changes from free to submerged, and vice versa. It was also found that no hysteresis effect on the calibration is observable in the 3-ft Cutthroat flume when moving from low to high submergence, or from high to low submergence.

The laboratory data demonstrate that previously published transition submergence, S_t, values do not accurately describe the hydraulic behavior of this Cutthroat flume because S_t is not constant for given flume dimensions – it varies with flow rate. Various criteria were applied to the laboratory data to define the curvilinear relationship of S_t with flow rate, thereby providing a more accurate application of the traditional free- and submerged-flow equations, in those cases where their continued use is desired. The observed S_t at the maximum discharge in each of the four throat widths was strongly correlated with the previously published S_t values.

INTRODUCTION

The methods and devices available for flow measurement in open channels are abundant, from procedures that only involve measure-at-a-glance, to complex structures inside canals. The selection of any of the many different methods and devices is contingent upon the required accuracy. One such device is a measurement flume. Flumes are often permanent structures and have the relative advantage of a low hydraulic head loss, compared to free-flow, sharp-crested weirs. Perhaps the most representative flume by its ubiquity is the Parshall flume (USBR 2001); nevertheless, the installation and construction of this flume can be complex, requiring a special calibration if the installed Parshall has a non-standard size.

On the other hand, the Cutthroat flume, so named because of its absence of a throat length in the structure (Skogerboe et al. 1993), presents some advantages compared to the Parshall flume due to its easy construction and installation, and its accuracy to measure discharge under free- and submerged-flow conditions.

[1]Alfonso F. Torres, Doctoral Student, Biological & Irrigation Engrg Dept. Utah State Univ, Logan, UT 84322-4105. atorres@cc.usu.edu. Phone: (435) 797-1139. Fax: (435) 797-1248.
[2]Gary P. Merkley, Professor, Biological & Irrigation Engrg Dept. Utah State Univ, Logan, UT 84322-4105. merkley@cc.usu.edu. Phone: (435) 797-1139. Fax: (435) 797-1248

Cutthroat Flume Characteristics

The Cutthroat structural design can be described as a rectangular flat-bottom flume with a narrowing section (throat), but lacking a throat length (Fig 1). This device is composed of two sections: the inlet converging section and the outlet diverging section. The narrowing section creates the transition from subcritical to critical flow (under free-flow conditions), a situation required to define a unique head-discharge relationship in which the downstream hydraulic conditions do not affect either the upstream water depth or the discharge.

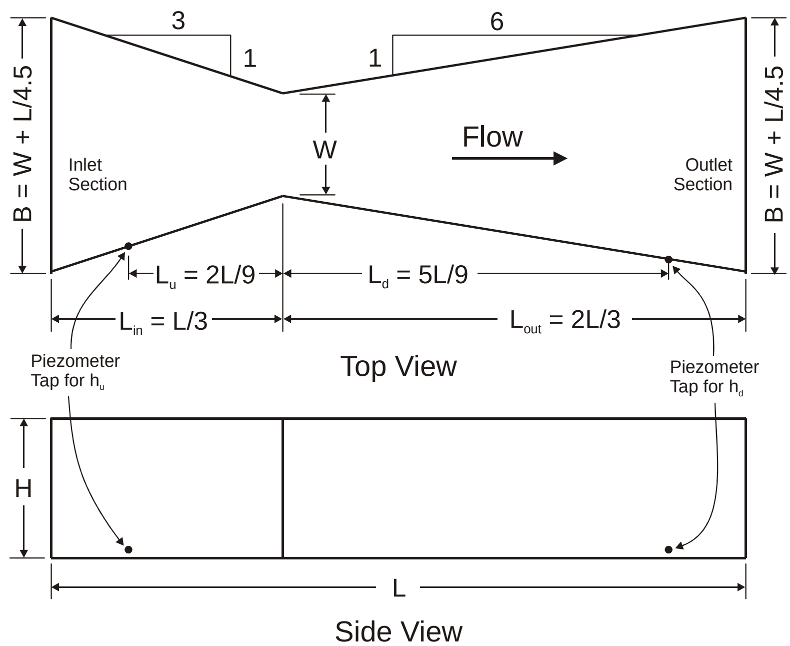


Figure 1. Cutthroat flume dimensions

Equation 1 relates water depth and discharge under free-flow conditions (Weber et al. 2006):

$$Q_f = C_f W h_u^{n_f} \tag{1}$$

where Q_f is the flow rate; C_f and n_f are calibration coefficients; and, h_u is the measured upstream water depth. The units of Q_f and h_u are typically m^3/s and m, or cfs and ft, respectively. The subscript "f" indicates free-flow conditions.

Under free-flow conditions, critical flow occurs in the vicinity of the flume throat, and any changes in downstream hydraulic conditions do not affect either the discharge or the upstream water depth. Under submerged-flow conditions, critical flow does not occur in the flume, and any change in the downstream water depth directly affects both the upstream depth and the discharge. Submerged-flow conditions require the measurement of both the upstream and downstream water levels, and the determination of the submergence value to estimate discharge. The measurement accuracy of the flume decreases under submerged-flow conditions.

Herein, submergence is defined as the ratio of downstream to upstream water depth. In equation form,

$$S = \frac{h_d}{h_u} \tag{2}$$

where S is submergence; h_d is downstream depth (m or ft); and, h_u is upstream depth (m or ft). The two depths are measured from a common elevation datum, and in the case of a Cutthroat flume this is the elevation of the floor (which should be level).

Transition submergence, S_t, is the value of S at which a free-flow equation will yield exactly the same discharge value as a submerged-flow equation for a given structure. It is the threshold which distinguishes between application of one equation or the other to define the relationship between flow rate and depth(s). Thus, the definition of transition submergence is an important part of the complete calibration for a flow measurement structure in open channels.

In the case of submerged-flow, the traditional calibration equation is (Skogerboe et al. 1967):

$$Q_s = \frac{C_s W (h_u - h_d)^{n_f}}{(-\log_{10} S)^{n_s}} \tag{3}$$

where Q_s is the flow rate; C_s and n_f are free-flow calibration coefficients; n_s is submerged-flow calibration coefficient, h_u and h_d are the water depths, measured upstream and downstream of the flume, respectively; and, S is the submergence. As in Eq. 1, the values of Q_s and h_u are depend on the chosen units (e.g. m^3/s and m, or cfs and ft).

Equation 3 involves downstream conditions when the actual submergence is greater than or equal to the transition submergence. Thus, the conditions at the diverging outlet section of the flume affect the upstream water depth, having effects on the upstream depth and the flow rate.

The transition submergence is determined by equating Eqs. 1 and 3, where $Q_f = Q_s$. The equation to define S_t can be written by equating the discharge values from the free- and submerged-flow equations (Weber et al. 2006):

$$C_f \left(-\log_{10} S_t\right)^{n_s} = C_s \left(1 - S_t\right)^{n_f} \tag{4}$$

where all of the variables were defined in Eqs. 1 and 2. Using a trial-error procedure, an S_t value can be determined from Eq. 4. The value of S_t has been considered to be unique for a given Cutthroat flume size; and published calibration tables give S_t values exclusively as a function of throat width (Skogerboe et al. 1967). However, recent research (Weber et al. 2006) supports the idea that the S_t value actually manifests significant variability, not only with throat width and flume length, but also with discharge.

Hysteresis Phenomenon

The hysteresis phenomenon was defined by the USBR (2001) as the maximum difference between water measurement readings of a quantity, in this case discharge, for a given value of submergence. For the present purposes, hysteresis is the potential difference in flow rate for a given submergence, depending on whether the submergence value was arrived at by increasing or decreasing the downstream water depth. It has been reported that a hysteresis phenomenon occurs in some Parshall flumes, causing a variation of +3% to +5% in measurement accuracy (USBR 2001). A study of submerged flow in Parshall flumes (Peck 1988) found considerable difference among discharges by a 1-ft Parshall equation and laboratory data, as shown in Fig 2.

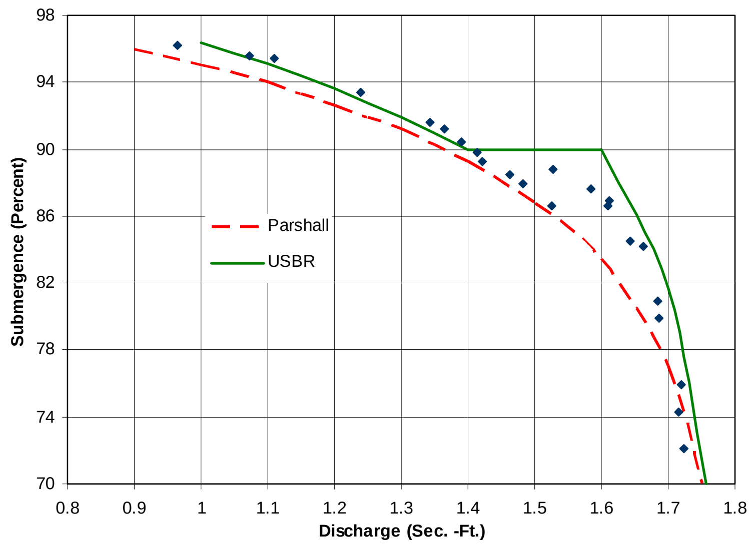


Figure 2**.** Relationship between discharge and submergence for a 1-ft Parshall flume (Peck 1988)

Figure 2 presents the relationship between the submergence and the discharge (cfs) for a given upstream water depth. The plotted data present a discharge discontinuity which is especially evident in the 0.78 and 0.88 submergence range, where hysteresis occurs (Q ≈ 1.52 cfs). This phenomenon has not been reported in the technical literature for a Cutthroat flume.

EXPERIMENTAL DESIGN

A 3-ft throat adjustable, acrylic Cutthroat flume was installed in a 24 x 3 x 3-ft rectangular flume at the Utah Water Research Laboratory, as seen in Fig. 3. The Cutthroat flume used in this research had a 3-ft length, with adjustable throat-width values of 4, 8, 12, and 16 inches. The Cutthroat flume also included piezometer taps located on the sidewalls. The piezometer taps were located 0.5 inches above the floor of the Cutthroat flume. The piezometric head at each tap was measured on a manometer board which was attached to the outside of the rectangular flume. Clear ¼-inch I.D. plastic tubes were installed from the taps to the manometer board.

Figure 3**.** Photograph of the laboratory setup

The 12- and 4-inch water supply pipes had sharp-edged, circular orifice plates connected to a differential manometer to measure the discharge entering the 3-ft rectangular flume during operation. The bed slope of the rectangular flume was measured and leveled to zero in the longitudinal and transverse directions. A tailgate at the end of the rectangular flume was used to change the water depth downstream. Four throat widths (W) were used, beginning with the 16-inch width, and progressively decreasing to 12, 8, and 4 inches. Fifteen different free-flow upstream depths, h_{uf}, (initial condition) were used for each throat width:

0.13, 0.20, 0.26, 0.33, 0.39, 0.46, 0.52, 0.59, 0.66, 0.72, 0.79, 0.85, 0.92, 0.98, 1.02 ft

Each series of measurements for a constant flow rate began with the tailgate in the completely lowered position: this provided free-flow conditions. The initial information was recorded: flume throat, water temperature, and supply water pipe used. Measurements of h_u and h_d were taken from a water manometer attached to the flume taps and additional manometer readings were taken from the supply pipe orifice plate to determine the flow rate after the 10-min time lag. Following this, the tail gate was raised slightly, and a new set of measurements were taken after observing that steady-state conditions have been reestablished. This process was continued for the given flow rate (which was constant) until the regime became submerged, at which point the tail gate continued to be raised, taking additional measurements until the upstream depth was nearly equal to the Cutthroat flume wall height, and/or the submergence exceeded 0.995.

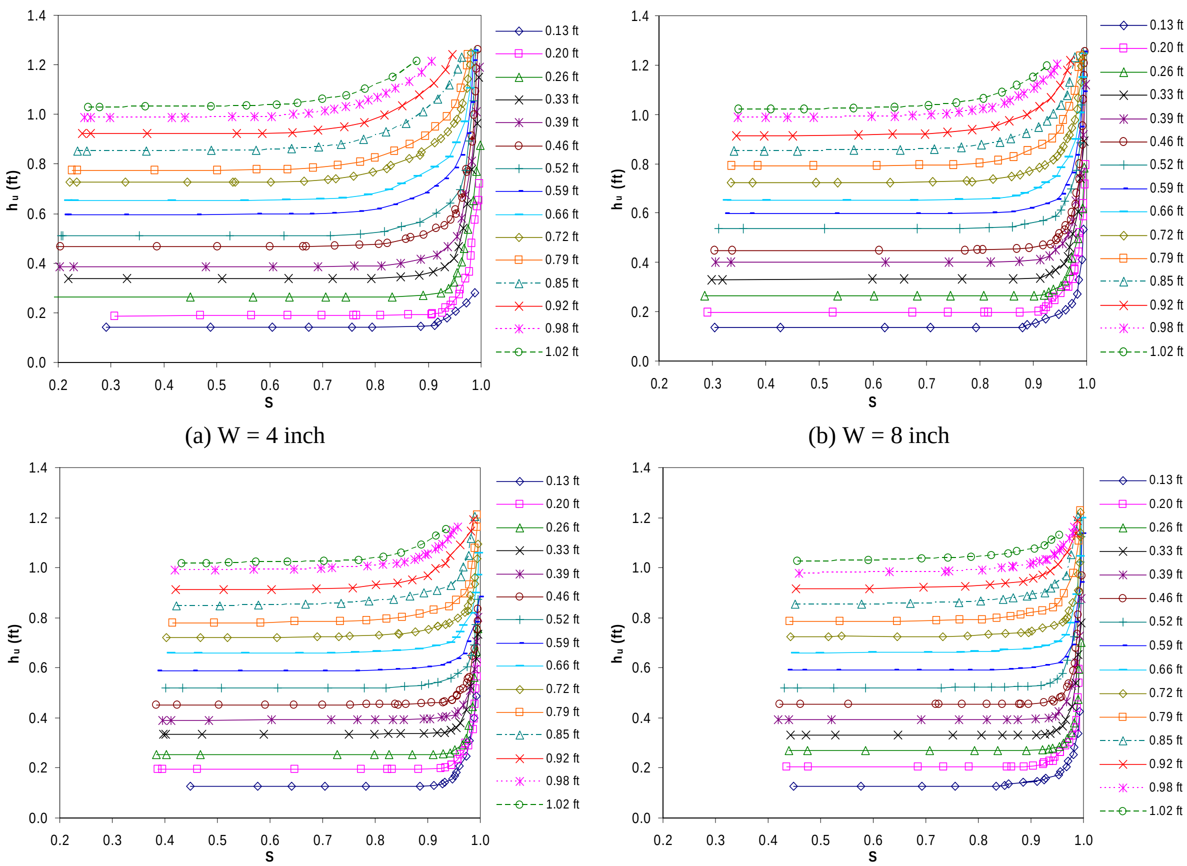
For h_{uf} values of 0.13, 0.46, 0.72, and 0.98 ft, once the maximum submergence value was reached, the tail gate was incrementally lowered, taking the same manometer measurements described above, until the regime was obviously free flow (it was never necessary to lower the tail gate completely to return to free-flow conditions). After completing measurements for all of the free-flow upstream depth, h_{uf}, values for a given throat width, the throat width was changed to the next smaller value and the same procedure was repeated. This was continued until the required measurements had been taken for all four throat widths on the 3-ft Cutthroat flume.

All measurements were taken under steady-state flow conditions. Thus, after a change in the tail gate position, a waiting period of at least ten minutes was found to be necessary to ensure steady-state hydraulic conditions before recording manometer readings. The 4-inch or 12-inch supply pipe to the 3-ft rectangular flume was used, as appropriate, depending on the flow rate.

RESULTS

Cutthroat Flume Hydraulic Data

The data obtained for each throat size are shown in Fig. 4. Each curve can be identified by the initial upstream water depth (h_{uf}) initially considered (0.13, 0.20, 0.26, 0.33, 0.39, 0.46, 0.52, 0.59, 0.66, 0.72, 0.79, 0.85, 0.92, 0.98, 1.02 ft). Some characteristics related to the data shown in Fig. 4 are listed below:



(c) W = 12 inch (d) W = 16 inch

Figure 4. Measured upstream water depth (h_u) and submergence (S)

- Each curve showed in the plots corresponds to a fixed and unique steady-state discharge. The "curves" in these plots are actually straight line segments which connect the data points;
- Each curve is composed of two sub-curves: one that describes a horizontal line (constant h_u value with respect to submergence, S) corresponding to free-flow conditions; and another sub-curve that shows an h_u increment related to the increase in submergence (submerged-flow condition);
- The threshold (transition) submergence between the horizontal and curved segments is different for each constant-discharge curve;
- The change from horizontal to curved lines in the curves is smooth and gradual, not presenting an abrupt change (i.e. no sudden change from free to submerged flow);
- Low-discharge curves (h_{uf} values of 0.13 and 0.20 ft) behave differently compared to the other curves for higher discharges for each of the four Cutthroat flume widths; and,
- Above a submergence of 0.95, the h_u values increase rapidly with submergence.

These characteristics help to define the data to be used in a transition submergence analysis:

- Omission of 0.13- and 0.20-ft data; and,
- Use of the rest of the data up to a maximum submergence of 0.95.

Traditional Free- and Submerged-Flow Equation Calibrations

With the collected data and the two constraints mentioned above, the calibration of the traditional free- and submerged-flow equation was accomplished. For the free-flow equation, the first upstream water depth measured per discharge and throat width was taken, giving 15 pairs of points (Q and h_u) per throat width. Subsequently, a logarithmic transformation and a linear regression were performed, whose resultant parameters were appropriately transformed in order to obtain the coefficients for the free-flow equation (Eq. 1).

The calibration of the submerged-flow equation was performed similar to the free-flow procedure. In this case, a logarithmic transformation of Eq. 3 was performed, giving Eq. 5:

$$-n_s \log_{10}(-\log_{10} S) + \log_{10}\left(C_s\right) = \log_{10}(Q_s) - n_f \log_{10}(h_u - h_d) \tag{5}$$

The data used to obtain the submerged-flow equation parameters were: discharge, submergence, and difference between upstream and downstream water levels (head differential), all with an $S \leq 0.95$ constraint. Based on the concepts and equations presented in the Introduction section, the coefficient values for the free- and submerged-flow equations were found.

Transition Submergence from the Free- and Submerged-Flow Equations

The estimation of transition submergence between these two flow conditions was accomplished using Eqs. 1 and 3. For the traditional equation forms, the transition submergence was found using a procedure described by Skogerboe et al. (1993). Nevertheless, it cannot be assumed that

S_t takes a single value for a given Cutthroat flume size, as can be seen in Fig. 4. Thus, despite the logical procedure followed for the traditional equations to obtain the submergence threshold value, the results do not correctly interpret the submergence threshold between free- and submerged-flow conditions. The estimated S_t values from the traditional and modified equations are presented in Table 2.

Table 2. Transition Submergence Values from the Free- and Submerged-Flow Equations

Equations	**W (inch)**			
	4	**8**	**12**	**16**
Published Values	0.58	0.67	0.75	0.82
Traditional FF and SF	0.65	0.73	0.79	0.77

Note: FF = free flow; SF = submerged flow

Equation Development

As seen in Fig. 4, the transition submergence cannot be defined as a single value as in traditional practice, given the visual difference among the laboratory data and a constant S_t value. This situation invites the development of new way to describe free- and submerged- flow conditions. The characteristics that the new equation must describe are:

- A horizontal line (constant h_u) for any submergence value in the free-flow range; and,
- A concave curve, where the h_u value increases as a function of the submergence and discharge in the submerged-flow range, approaching the vertical at S = 1.0.

Given the characteristics that the new flow equation must account for, the empirical equation selected (among several alternatives) for this research is:

$$h_u = h_{uf} + \left(\frac{aQ + b}{\left[\ln\left(cQ + dS^e \right) \right]^f} \right) \quad (6)$$

The values of h_u and Q were described by Eqs. 1 and 3, h_{uf} is the upstream water depth for free-flow conditions; and, the letters a, b, c, d, e, and f represent fitted equation parameters. The value of h_{uf} is defined by Eq. 1. The results from the statistical analysis are shown in Table 3, and the calibration parameters for Eq. 6 are given in Table 4.

Table 3. Statistical Equation Analysis Summary (all throat widths)

			Percentage of total data fitted		
Total data points	**Mean r^2**	**SSR**	**Error < 1%**	**Error < 3%**	**Error < 5%**
706	0.999	0.032	75%	97%	99%

Notes: r^2 is the coefficient of determination. SSR is the sum square of residuals

Table 4. Calibration Parameters for Eq. 6

	Equation 6 Parameters					
W (in)	**a**	**b**	**c**	**d**	**e**	**f**
4	5.47	-0.29	10.60	3.54	-20.15	2.66
8	13.50	-2.59	0.05	13.61	-10.65	4.32
12	8.11	-0.11	0.03	26.05	-15.77	3.94
16	0.89	0.03	0.04	13.58	-19.72	3.09

Transition Submergence from the Newly Proposed Equation

Once the proposed equation was calibrated for each of the four throat widths, it was possible to define the transition submergence for each. The value of the submergence that was considered as the threshold between free- and submerged-flow conditions was specified as the submergence value that, when used in the derivative of the equation, gives a specified slope value (Eq. 7).

$$S_0 = S_t \Leftrightarrow f'(S)\Big|_{S=S_0} = m \tag{7}$$

where S_o is the submergence value to be considered as the transition submergence (S_t), considering that when S_o is used in the first derivative of the equation, the result is a fixed slope value, m. One important parameter at this point is the derivative value of the equation. This value should be constant for all the equations regardless of the Cutthroat flume throat width, and must accurately define the submergence threshold for all the curves to be considered as the transition submergence. Furthermore, the value of the slope to be selected should improve the accuracy of the traditional free- and submerged-flow equations by the use of the submergences estimated based on the selected slope.

To determine the most appropriate slope for the definition of transition submergence, five different values were considered: 5.0%, 7.5%, 10.0%, 12.5%, and 15.0%. Based on the submergence values obtained using these slope values, SSR values from the traditional free- and submerged-flow equations were calculated. The results are shown in Figs. 5 and 6.

From Fig. 5, it is evident that the SRR values increases for the minimum slope value (right side of Fig. 5) since the submerged-flow equation is in the free-flow range. The SSR values indicate that the traditional free- and submerged-low equations reach a minimum SSR value with a slope value of 10%. This indicates the appropriateness of Eq. 6 as model that adequately represents the measured data. From these results (Fig. 6), it is evident that Eq. 6 more accurately describes the location where transition submergence occurs along the curves described by the laboratory data. This characteristic, plus the high correlation among predicted and measured S versus h_u and discharge data, indicates the advantage of applying Eq. 6 instead of the separate free- and submerged-flow equations which have been traditionally used to calibrate 3-ft Cutthroat flumes.

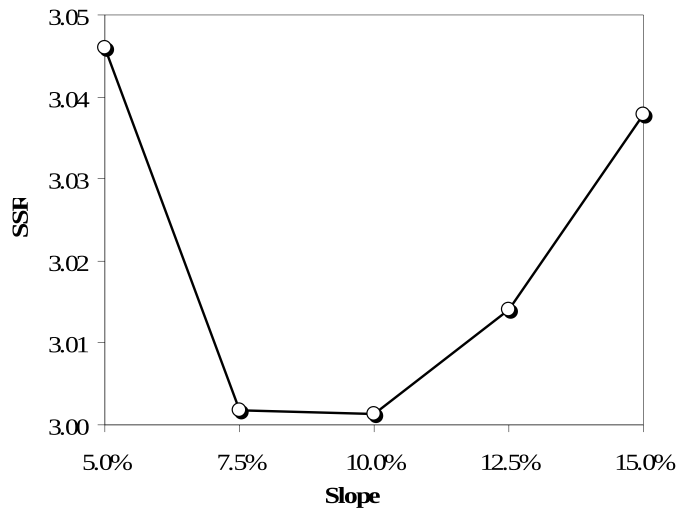


Figure 5. Accumulated SSR from the proposed equation per slope value (all throat widths)

Hysteresis

Based on the data collected during this research, it was possible to analyze the existence (or lack thereof) of the hysteresis phenomenon, considering data of those discharges for which the tailgate at the end of the rectangular flume was raised and lowered. These discharges, expressed by the upstream water depth, are the following for each of the four throat widths: 0.20, 0.46, 0.72, and 0.98 ft. The criterion behind this 4 discharge selection was to adequately distribute the data collection for hysteresis among all 15 upstream water depths considered for the research, in order to accurately describe the hysteresis effects, in case this phenomenon really occur in Cutthroat flumes. The data are given in Fig. 7.

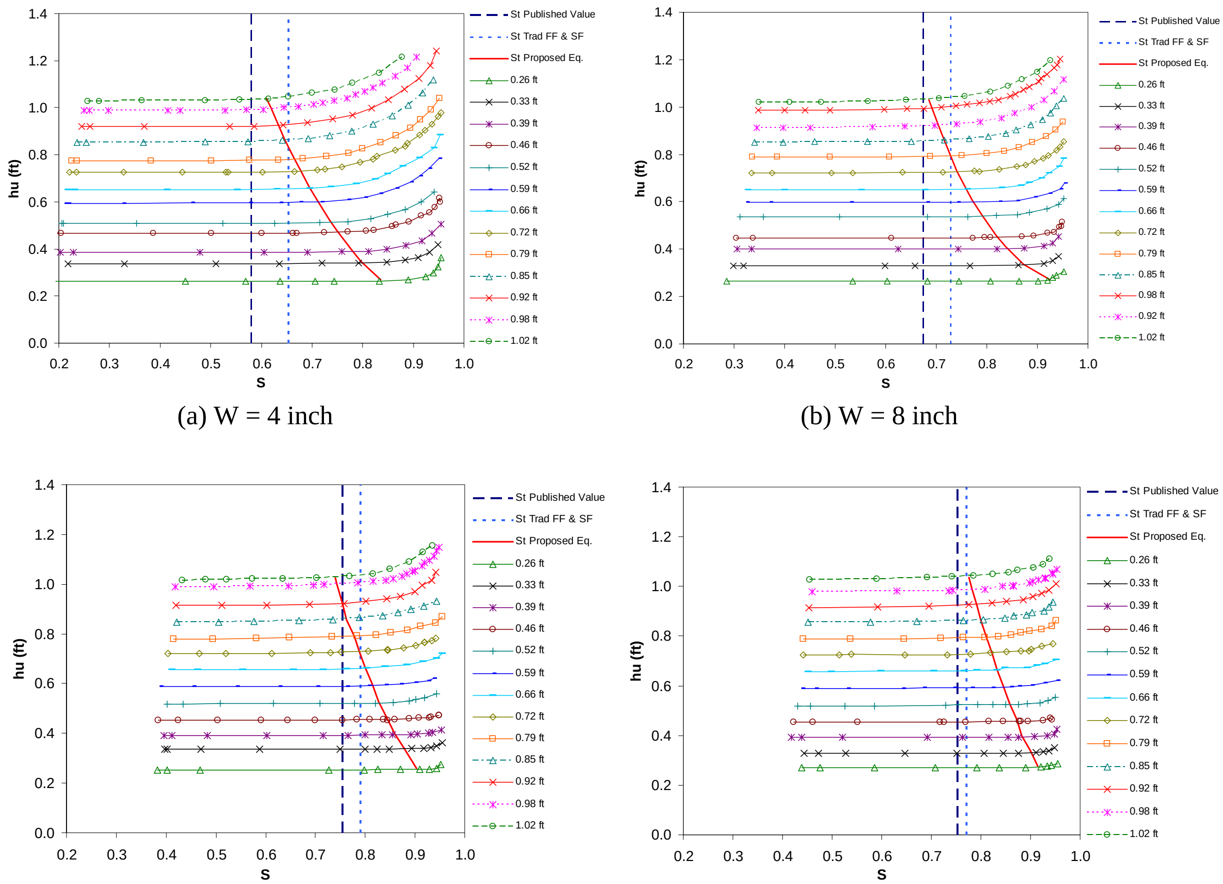
It is easy to observe (Fig. 7) that a detectable hysteresis phenomenon does not occur for any of the data values collected for the 3-ft Cutthroat flume. The minimal differences that appear at the data plots are related to the water movement by effect of the hydraulic jump downstream of the Cutthroat flume, and to the accuracy of the readings done, being these differences not significant to assure in a definitive way that this phenomenon should be considered present at Cutthroat flumes.

SAMPLE APPLICATIONS

The following are examples of the recommended use of these research results in practical flow measurement applications. The example is for the traditional forms of the free- and submerged-flow equations using transition submergence values from Eq. 6 as threshold between free- and submerged-flow conditions.

Use of Submergence Values from Eq. 6

The initial condition for this procedure is the data collection under free- and submerged-flow conditions as described in the Introduction section. Based on these data, the calibration of the traditional free- and submerged-flow equations and Equation 6 can be done. In this example, data from the 4-inch Cutthroat flume throat width will be used. Based on the results of the calibration previously done, transition submergence values from Eq. 6 are obtained using a fixed slope of 0.10 and several upstream water depths, h_u, creating an S_t range from small to the large discharges, and obtaining a graph similar to that shown in Fig. 8.



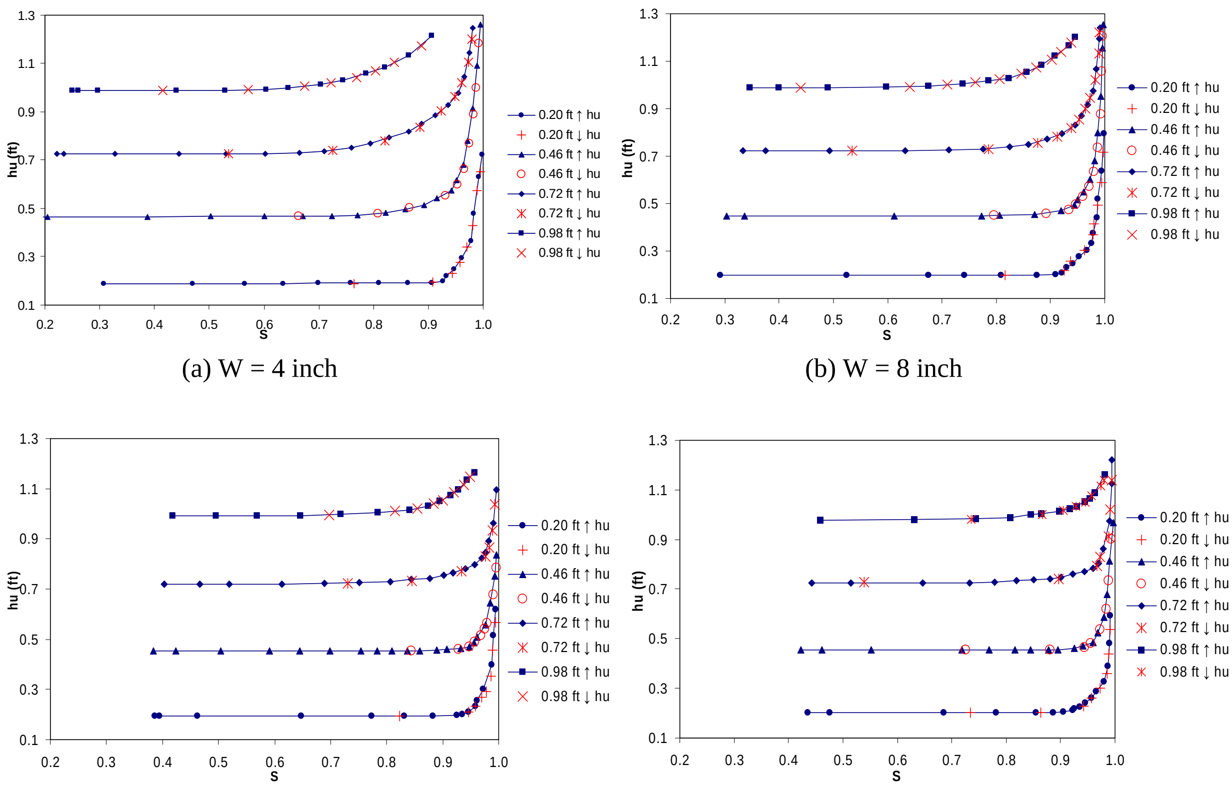
(a) W = 4 inch (b) W = 8 inch

(c) W = 12 inch (d) W = 16 inch

Figure 6. S_t behavior from published values and traditional and proposed equations

In Fig. 8, the S_t - h_u curve for a 4-inch throat width allows the differentiation between free- and submerged-flow regions where the respective traditional equations (Eqs. 1 and 3) can be applied. Also, it is possible to establish an accurate mathematical relationship between S_t and h_u, as shown in Fig. 8, obviating the need for a graphical determination of S_t and the water flow condition to consider.

To estimate the discharge in the 4-inch throat width using the S_t values from Eq. 6, it is necessary to measure the water depth both upstream and downstream in the Cutthroat flume. In this example, the data obtained for two Cutthroat flumes with W = 4 inches were:



(a) W = 4 inch (b) W = 8 inch

(c) W = 12 inch (d) W = 16 inch

Figure 7. S-h_u curves - increasing (↑) –decreasing (↓) submergence

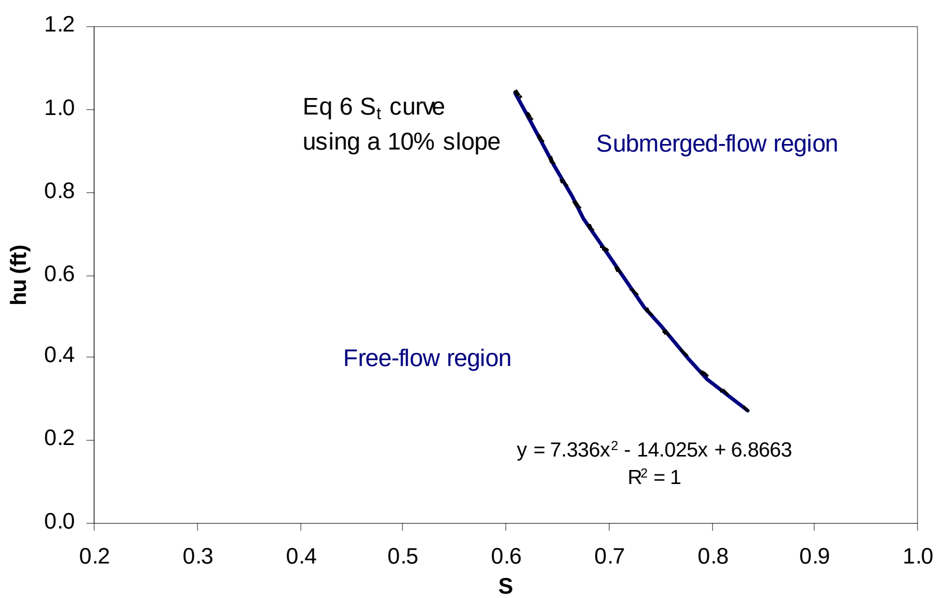


Figure 8. Equation 6 S_t values and correlation (W = 4 inches)

Cutthroat 1	Cutthroat 2
h_u : 0.56 ft, h_d : 0.24 ft	h_u: 0.70 ft, h_d: 0.60 ft

Then, the submergence is calculated for each are:

S : 0.43	S: 0.86

Figure 9 is obtained by plotting these two points on Fig. 8. It can be observed that the flow condition for Cutthroat flume 1 is free-flow, and the second flume is in a submerged-flow condition. Thus, it is possible to apply the respective equations to determine the discharge in each case:

For Cutthroat flume 1:

$$Q_f = C_f W h_u^{n_f} = 4.197(0.333)(0.56)^{1.685} = 0.527 \text{ cfs} \quad (8)$$

For Cutthroat flume 2:

$$Q_s = \frac{C_s W(h_u - h_d)^{n_f}}{(-\log_{10} S)^{n_s}} = \frac{2.595(0.333)(0.70-0.60)^{1.685}}{(-\log_{10} 0.86)^{1.335}} = 0.660 \text{ cfs} \quad (9)$$

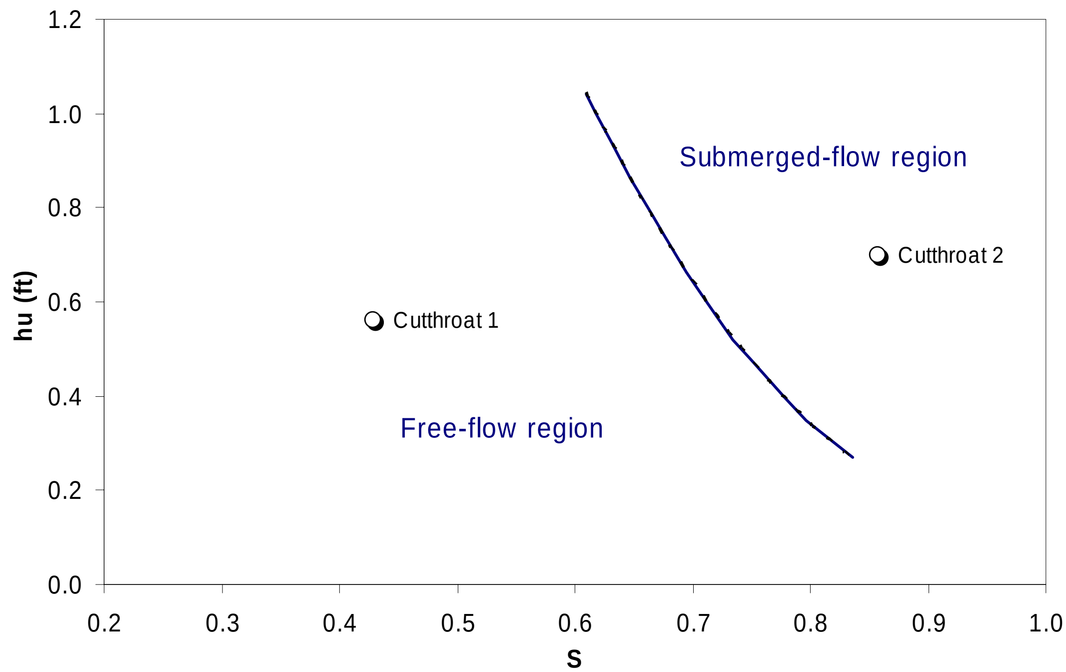


Figure 9. Equation 6 S_t values and sample Cutthroat flume data (W = 4 inches)

CONCLUSIONS

The analysis of the 3-ft Cutthroat flume collected data suggests several notable conclusions: first, observation and analysis did indicate that transition submergence, S_t, varies with discharge for a given Cutthroat flume length and width, thereby refuting the assumption of a single S_t value for each flume size, as previously believed. The transition submergence values are higher for small discharges, decreasing with and increase in flow rate. It was also noted that the transition submergence decreases at very small flow rates. The range of transition submergence values was found to be different for each Cutthroat flume throat width. Previously published transition submergence values are mathematical solutions for the intersection of traditional free- and submerged-flow equations, and do not accurately represent the hydraulic behavior of the S_t parameter, in general.

Second, a transition submergence accuracy analysis for the existing free- and submerged-flow equations was performed. The traditional equations demonstrated their inability to accurately describe the expected threshold submergence.

Third, based on the previous results, it became necessary to develop a new equation that can describe adequately the S versus h_u behavior for free- and submerged-flow conditions. From several alternatives, Eq. 6 provides an excellent S_t fit. Using the first derivative of the Eq. 6, and analyzing several slopes, it was determined that the best slope value is 0.10 (10%), gives the minimum error for the free- and submerged-flow equation using the data collected.

Fourth, given the excellent fit obtained among the values from Eq. 6 and laboratory data (discharge, submergence, and water depths), it is possible to use this equation to calculate the flow rate without the need to apply separate free- and submerged-flow equations, and without the need to determine transition submergence.

Fifth, an analysis of the hysteresis phenomenon was performed, whereby it was determined that there is no observable presence of this phenomenon in the Cutthroat flume sizes considered in this experiment. The absence of this phenomenon indicates that the water depth measurements in Cutthroat flumes will have a unique discharge correspondence regardless of whether the submergence may be increasing or decreasing, provided the flow conditions are steady.

Lastly, the results of this study are for 3-ft Cutthroat flumes, but the same hydraulic analysis is likely to be valid for Cutthroat flumes of different lengths and throat widths, at least within the size ranges for which calibration data are already available. This analysis will probably also be valid for various other open-channel measurement flumes, such as Parshall flumes, because the same traditional free- and submerged-flow equations have been used to calibrate this and other flume geometries.

RECOMMENDATIONS

First, it is recommended to repeat this experiment under non-laboratory conditions (e.g. Cutthroat flumes installed in irrigation canals), regardless of the materials used for their constructions (concrete, metal, bricks, others) in order to have a better understanding of the hydraulic behavior of the transition submergence. Second, based on the methodology followed in this research, similar experiments should be done with other type of flumes and weirs (e.g. Parshall flumes, broad- and sharp-crested weirs) to determine whether the transition submergence has the same or different behavior than the reported in this research. The same forms of the free- and submerged-flow equations which have traditionally been used to calibrate Cutthroat, Parshall, and other open-channel measurement flumes suggest that the curve-fitting analysis presented herein could also apply to the accurate calibration of other flume sizes and shapes. Also, it would be useful to determine whether Eq. 6 is also applicable to the calibration of other Cutthroat flume sizes, and of different flume geometries, such as those of Parshall flumes.

Finally, it is necessary to develop a new unique discharge versus water depth equation that can accurately describe the relationship among flow rate, submergence, and water depths, avoiding the need to use two equations and regardless the free- or submerged-flow condition or the value of transition submergence. Equation 6, proposed in this research, appear to be an excellent starting point in both the development of improved and simplified equations for measurement flume discharge calibrations, but it is envisioned that there may be other equation forms which can fit the data even better, perhaps up to submergence values beyond 95%.

REFERENCES

Peck, H.W. (1988). *Study of Submerged Flow in Parshall.* PAP-535, United States Government Hydraulic Branch.

Skogerboe, G.V., Hyatt, L., Anderson, R., and Eggleston, K. (1967). *Design and Calibration of Submerged Open Channels Flow Measurement Structures Part 3 – Cutthroat Flumes,* Utah Water Research laboratory, College of Engineering, Utah State University, Logan.

Skogerboe, G.V., Ren, L., Yang, D. (1993). *Cutthroat Flume Discharge Ratings, Size Selection and Installation*, International Irrigation Center, Biological and Irrigation Engineering Department, Utah State University, Logan.

USBR. (2001). *Water Measurement Manual*, 3rd Ed., Revised. United States Department of Interior, Bureau of Reclamation, Washington, D.C.

Weber, R.C., Merkley, G.P., Skogerboe, G.V., Torres, A.F. (2006). *Improved Calibration of Cutthroat Flumes*. Irrig. Sci., Springer-Verlag, December, 2006.

PRACTICAL IRRIGATION FLOW MEASUREMENT AND CONTROL — AN UPDATE

John A. Replogle[1]

ABSTRACT

Previous discussions concerning practical technologies that can encourage farmers to adopt practices supporting sustainable irrigated agriculture are updated. Important among these are convenient water measurement and control techniques. These techniques need to be available not only to the farmers, but also to the delivery system operators that make the system responsive to the on-farm needs. Improved irrigation planning and management techniques depend heavily on accurately controlling and quantifying water deliveries. Automation places a further burden on reliable operation of primary water measuring and flow control equipment. Many simple constructions and operating procedures can be provided to farmers and irrigation-delivery-system operators that offer considerable convenience at small expense and can be included in automation upgrades to improve reliability. Problems of reliability are aggravated if equipment is not easily field checked for proper functioning. Many observable clues, when they do exist, go unrecognized by inadequately trained personnel. This compilation of practices and design suggestions should help the operator assure valid measurement data and control functions. These suggestions are intended to make these devices easier to use, easier to verify, and more economical to construct and install. The techniques and devices discussed included: (a) accurate and convenient zero setting for weirs and flumes; (b) pressure-transducer field checks; (c) easy-to-use scales for orifice and Venturi meters; (d) wave suppressors for canals that flow at variable depths; (e) method for measuring Manning *n* values; and (f) flow-profile visualization using rising-bubble techniques to evaluate canal flow conditioning. Also included is a discussion of some pipe flow conditioning ideas used in field practice for devices installed in adverse conditions.

INTRODUCTION

Improved irrigation planning and management techniques depend heavily on accurately controlling and quantifying water deliveries. Modernization of systems involving mechanization and automation place a further burden on reliable operation of water measurement and control equipment. Irrigation control and measurement can potentially be done in this age of technology with so-called “high tech” methodology. Many of these methods may be difficult to support both technically and economically in an agricultural environment. However, several low-cost and practical technologies exist that can encourage adoption of practices supporting effective water use, modernization and sustainable agriculture. User understanding of the proper application, installation, use, and maintenance of control and measuring devices is generally less than desirable. Many observable clues, when they do exist, go unrecognized by inadequately

[1] Research Hydraulic Engineering Collaborator; US Arid Land Agricultural Research Center, 21881 North Cardon Lane, Maricopa AZ 85238; jreplogle@uswcl.ars.ag.gov.

trained field personnel. Not all of the problems can be traced to the user. Reliability problems arise because much of the equipment is not readily field checked for proper function.

This paper deals with a compilation of practices and design suggestions to assist measurement personnel to recognize valid measurements and control functions. Thus, discussed herein, are some useful procedures and designs to make these devices economical, easier to use, and more readily verified.

REDUCING ERRORS AND MISTAKES

Flow Measurement Errors For Canal Deliveries

Measurement errors can be systematic (bias), random, or mistakes. Random errors can be treated statistically and affect the level of assurance that can be placed on a reading or group of readings. Systematic, or bias, error, if discovered, can often be used to correct past records. Mistakes do not lend themselves to any particular method of recovering or correcting data. Wahlin, et al, 2000, discusses treatment of errors usually appropriate to canal measurements. They review methods of checking for bias errors and the statistical knowledge that random errors tend to zero with large samplings. Thus, rather large flow-rate variations in individual readings may still render relatively accurate volume results over long time periods of record, once systematic errors are satisfactorily laid to rest. This knowledge will be referred to in the following discussions of flow meters and their uses.

Zero settings Inaccurate zero settings for flume and weir wall-type gages and recording devices are a primary source of systematic error. Eliminating the need for precise leveling is among conveniences that make a flume easily portable. Previous work showed that long-throated flumes are very forgiving. That is, they can be sloped upward slightly in the direction of flow without changing the discharge equation significantly (Replogle et al. 1987). However the upstream depth gage must be referenced always to the elevation of the throat floor near the out-fall end. A point on the centerline of the flume about one-quarter of the throat, or crest, length from the outlet end, works well for the zero-reference elevation. For portable flumes, if a wall gage is used at the usual upstream measuring point in the approach section, then the gage will not remain properly “zeroed” to the reference elevation in the throat if the flume is not level both longitudinally and laterally. To avoid this, an offset stilling well is useful. With it, the water surface from the upstream gage location is siphoned to a point above the zero reference, where the distance to the throat floor is then observed and small slopes are largely compensated. This general method will also be discussed below for its additional utility with non-portable flumes.

Sidewall gages marked directly in flow rate usually produce readings accurate enough for irrigation purposes and reduce the chance of using the wrong flow table or equation.

If a stilling well and recording instrument are to be used, then convenient and accurate zero setting is needed to properly reference the instrument. Avoid the so-called “drain-down-to-zero” method commonly found to be used in field practice, because it is not accurate enough for most small field channel installation due to surface tension effects that introduce a systematic error (Bos et al, 1991).

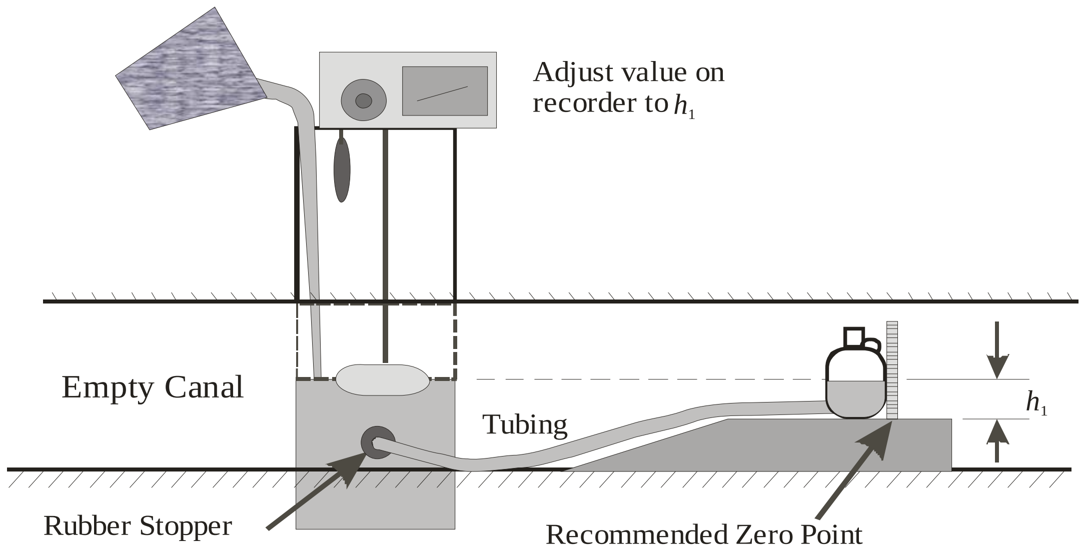


Figure 1. Method to Zero-Reference a Flume or Weir in a Dry Channel for Portable and Permanent Flumes

A simple and accurate scheme to zero-reference a portable or permanently installed flume is a slightly modified version of that described in Bos et al, 1991. Referring to Figure 1, use plastic tubing and a rubber stopper to connect the bottle container to the stilling-well tap hole. Fill the stilling well with water and allow it to partly fill the container, which is placed at the sill-zero location. Check for bubbles in the line to make sure the water level in the container accurately reproduces the water level in the stilling well. Measure the distance, h_1, from the sill surface to the water level in the container and adjust the value on recorder to h_1. If possible, check another flow level to assure that mistakes are eliminated. A common mistake with chart recorders is that the technician may set the physical reading of h_1 on the chart instead of the gear-reduced chart value of h_1.

This procedure is usually more convenient than using surveying methods that require trying to determine the stilling well water surface with a surveying rod. This procedure should be adaptable to most weirs and flumes. It allows the stilling well to be detached from a portable flume and readily re-zeroed after movement. This makes installation convenient and flexible because the stilling well can be located upstream, downstream, or in the canal bank. The primary requirement is that the pressure sensing (stilling well tap) is at the prescribed upstream location and connected by tubing to the stilling well, wherever it is placed.

A static-pressure probe, Figure 2 can conveniently be used to achieve a correct instrument zero in a flowing canal. The probe is placed in the flowing canal upstream of the flume or weir in the designated cross-channel plane for depth sensing, Figure 3. The static-pressure probe should be oriented parallel to the approach flow, but can be on the channel bottom, sidewalls or midstream at any depth below the surface.

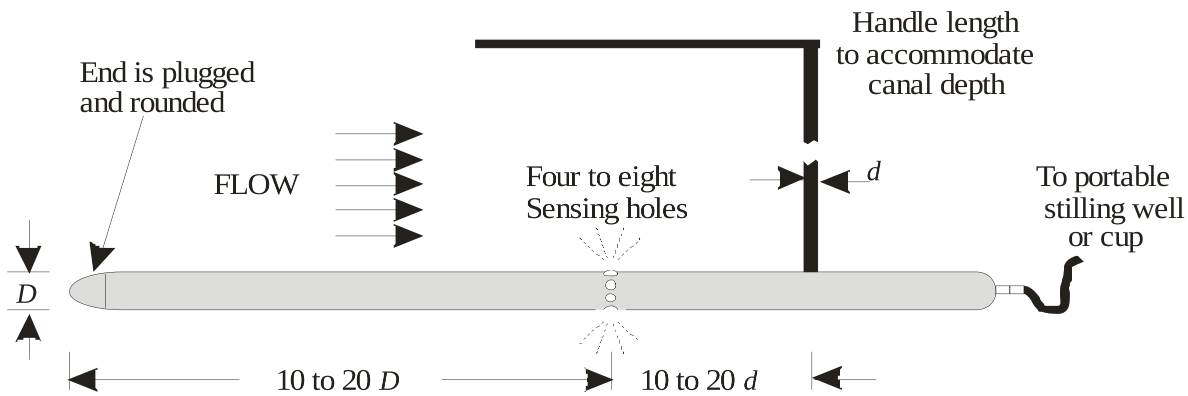


Figure 2. Static-Pressure Tube has Several Useful Functions in Canal Operations and Management

Staff Gages   Staff gages, usually wall mounted, are recommended at all depth sensing locations regardless of the attending electronic detection and transmission because it provides immediate field data validation to reduce mistakes and detect malfunctions.

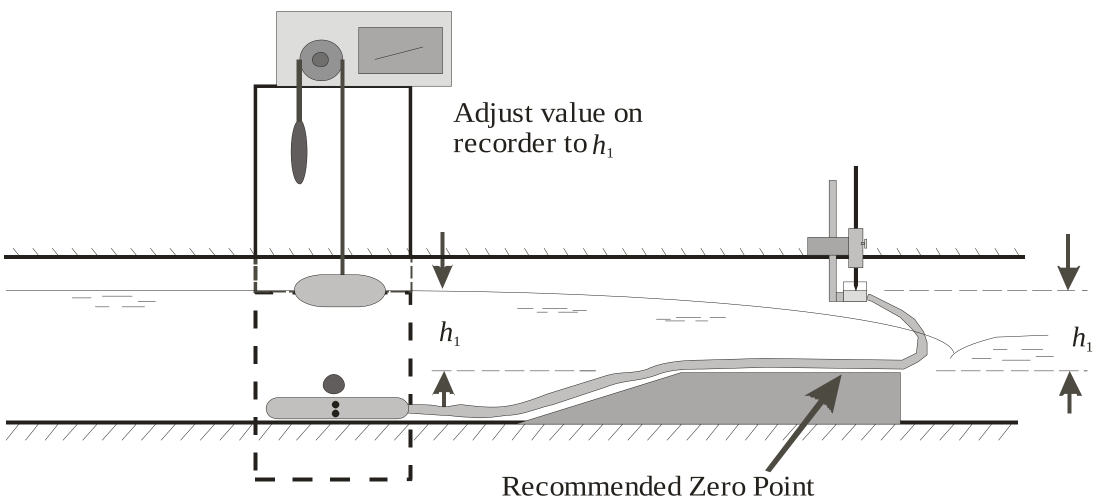


Figure 3. Method to Zero-Reference a Flume or Weir in Flowing Water

Installation Precautions for Flumes and Weirs   Stilling wells used with weirs and flumes, or to simply detect canal depth, often do not indicate the correct water depth. Figure 4 illustrates a common problem and suggested corrections. For a pipe protruding into the flow, such as might be encountered in an earthen channel, a round or rectangular plate large enough to provide smooth flow past the pipe entry, usually with an approach length of 10 to 20 pipe diameters upstream and 3 to 5 diameters downstream will suffice. A plate that is longer in the upstream direction, and with the upstream edge tapering into the stream bank at not more that a 3:1 angle, may be needed to avoid catching debris. An alternate is to use a static-pressure probe (Figure 2).

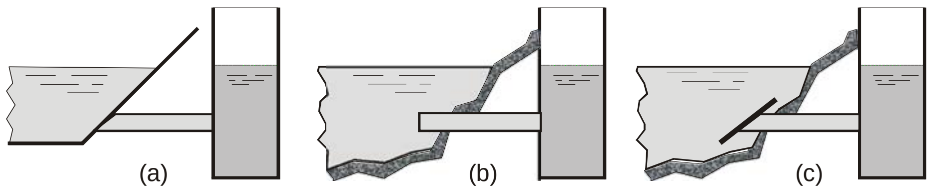


Figure 4. Stilling Well Installations: (a) Pipe Correctly Cut Smooth at Channel Boundary Wall; (b) Pipe Incorrectly Protrudes into Flow; (c) Correction Using a Plate Added to Pipe to Simulate a Channel Wall

Pressure-Transducer Field Checks Water-submersible, temperature-compensated pressure transducers are increasingly being used for detecting water depth in canal systems. These pressure transducers can typically detect depth to an accuracy of ±3 mm. For depths in small canals, this random error represents an uncertainty of 6% for a 150 mm instantaneous depth reading, and even more for shallower depths. However, if total delivered volume is more important than instantaneous readings, the many readings involved for the volume tend to reduce this random uncertainty to zero, even for the shallow flows, and volume records can be expected to be well within ±5%.

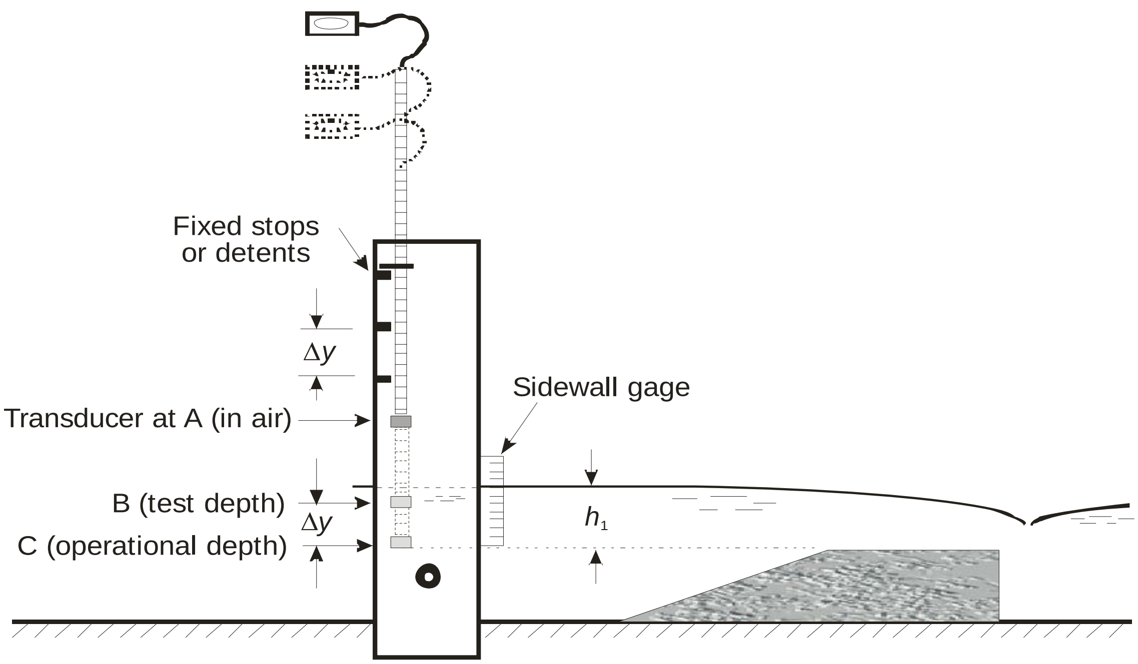


Figure 5. Pressure Transducer on Movable Rack

To render submersed transducers conveniently field checkable, the device can be mounted on a rigid, but movable rack with detents, or stops, at the operating depth, some known other depth, and in the air. These mounting detents can be as simple as "eye" bolts on the wall and screws on a sliding rod. To check the installation, the transducer output is read in the stilling well while:

- In the air, where the zero-pressure reading, e_0, is noted:
- At operating depth, where an output reading, e_1, is noted in any scale units without particular regard to span or zero setting; and
- At a known distance, Δy, above or below the operating depth position, where another output, e_2 is noted.

$$h_1 = \frac{e_1 - e_0}{\left(\frac{e_2 - e_1}{\Delta y}\right)}$$

This value of h_1 can be referenced to the zero elevation of the flume, weir, or other depth-indicating device, such as a permanently mounted wall gage. Thus the field technician can quickly verify proper function and can calibrate the pressure transducer in the field environment. For convenience of description, the operating position of the transducer is shown at the zero elevation reference in Figure 5. This is not necessary as long as the transducer-zero offset is determined, perhaps by surveying methods, and is applied to the value of h_1.

Float Activated Recorders Float operated recorders have a long history and are well established (Bos, 1989; Bos et al, 1991). Inappropriately small diameter floats may introduce unacceptable errors of recording and may have variable responses during depth reversals due primarily to instrument friction. The main design feature for floats is the float diameter. Usually 15 cm or larger diameter is selected to overcome most instrument friction effects. It should be pointed out that float weight does not influence the operation except as it might cause more bearing friction. The cross-sectional area, usually a diameter of the float, is the important dimension. Thus, in concept, counter-weighted concrete blocks could be used if they are suitably coated to reduce variable water absorption. Usually cylindrical floats serve as well or better than ball floats. Glass jugs, partly filled with rocks to assure that they stay upright, can be used. Plastic jugs are to be avoided, because they may change shape and introduce a systematic zero shift. Rounded or conical tops discourage a resting place for frogs, mice, and accumulated dust and dirt that can introduce systematic error.

PRACTICAL FIELD EQUIPMENT AND PROCEDURES

Special Applications To Canal Operations

Wave suppression in canals Excessive waves in small canals are usually caused by a jet entry from a sluice gate or by a waterfall situation. The unstable surface can be 10 to 20 cm high and extend for tens of meters downstream, making the reading of sidewall gages on flumes and weirs difficult. For canals that usually flow at a fixed level, a firmly fixed, roof-like structure that penetrates the flow by as little as 10% of the flow depth, used in conjunction with a floor and wall projections of about the same proportions, have been effective in reducing the wave height to as little as 10 % of the original wave problem. The length in the flow direction of the roof-like structure has not been well established, but two or three surface wavelengths are recommended. Field observations would suggest that this length would be about equal to the flow depth, Figure 6 (Replogle, 1997).

Figure 6. Wave Suppression in Small Canal.

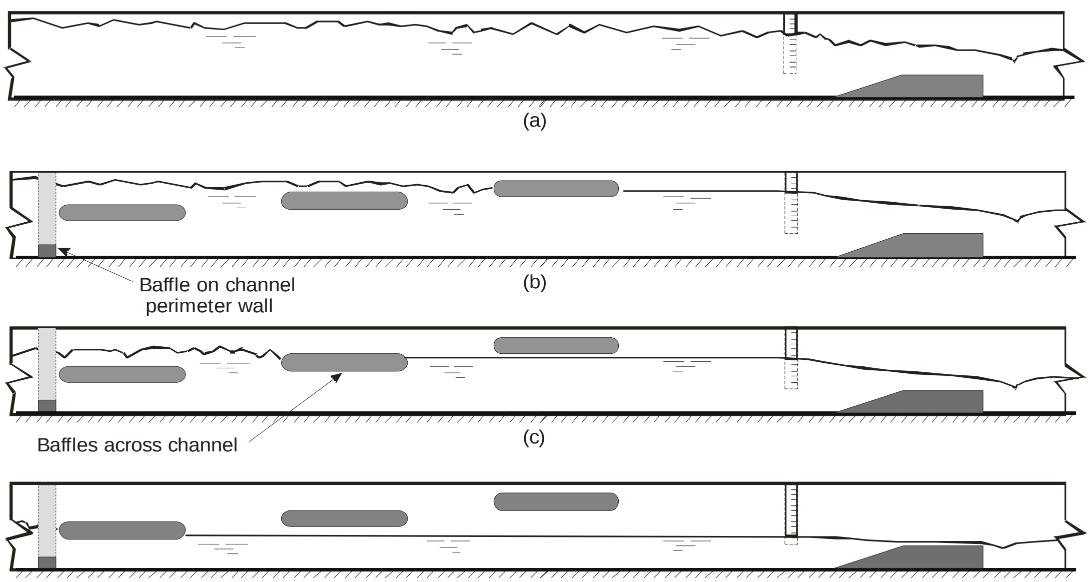


Figure 7. Wave Suppression for Variable Depth Flow. Top (a): Untreated Canal. (b),(c),(d): Typical Behavior at Various Flow Depths

To suppress waves in canals that do not always flow at the same depth, a staggered set of baffles, Figure 7, has been successfully used in a rectangular laboratory channel (1.25 m wide flowing up to 0.5 m deep). The original channel with no baffles is represented in Figure 7(a). Typically a perimeter baffle is added that may have dimensions of about one-tenth the channel depth. This may be made of a row of bricks or an angle iron. The thickness in the flow direction is not critical. The cross-channel baffles are rounded on at least the upstream end to help shed floating debris. Each baffle thickness should not exceed about 25% of the channel depth and should be placed in elevation to slightly overlap the previous baffle. The baffles should proceed in increasing elevation in the direction of flow, as shown, otherwise flow would go over the baffle and the resulting waterfall would recreate new waves.

Flow conditioning to improve meter performance Frequently, water is discharged through a partly open gate valve producing a jet along a pipe boundary. The jet effects may be aggravated by a pipe bend as depicted in Figure 8. The insertion of a large orifice on the order of $B = 0.9$, which is not well suited for use itself as a flow meter because it produces a small differential-head reading, will disperse the boundary jet across the flow. This results in an improved flow profile being presented to the downstream meter. A slightly larger gate opening compensates the slight increase in head loss. Although the resulting profile has reduced both flow jetting and spiraling, additional vanes protruding from the pipe walls may further improve the results, particularly for propeller meters.

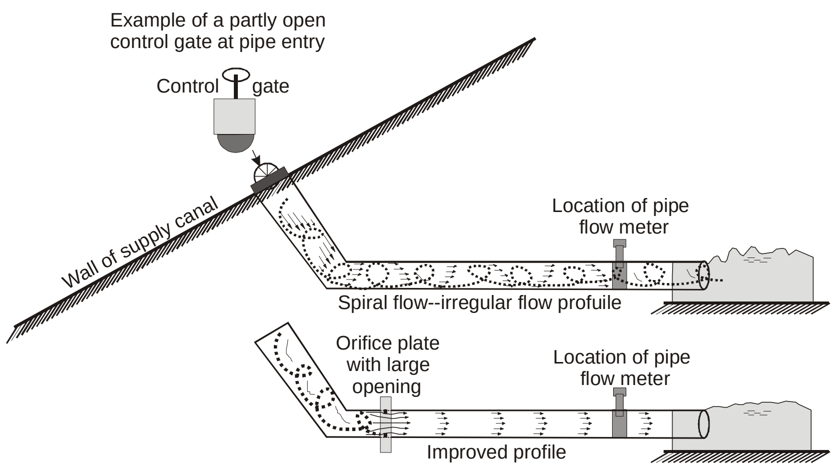


Figure 8. Orifice With Large Opening ($B = 0.9$) is used to Condition Flow for Downstream Meter

Simple Constructions

Several suggested special tools and procedures are described in following section. Most can be fabricated in farm shops.

Simplified Flume Constructions Low-cost, but accurate canal flow measurements are provided in the simplified construction methods illustrated in Figure 9. Most of the parts including the adjustable wall gage arrangement can be constructed in some farm shops or a local sheet-metal shop. The wall gage is in two parts as shown. The marked metal gage can be made by using WinFlume (Wahl, et al. 2005) first to print a direct-discharge, rate-indicating paper gage. This paper gage is then taped to a sheet metal strip that will fit into the holding bracket as shown. A chisel and punch is then used to make permanent markings on the sheet metal strip. This marked sheet metal strip can be easily adjusted to the correct zero elevation using surveying methods.

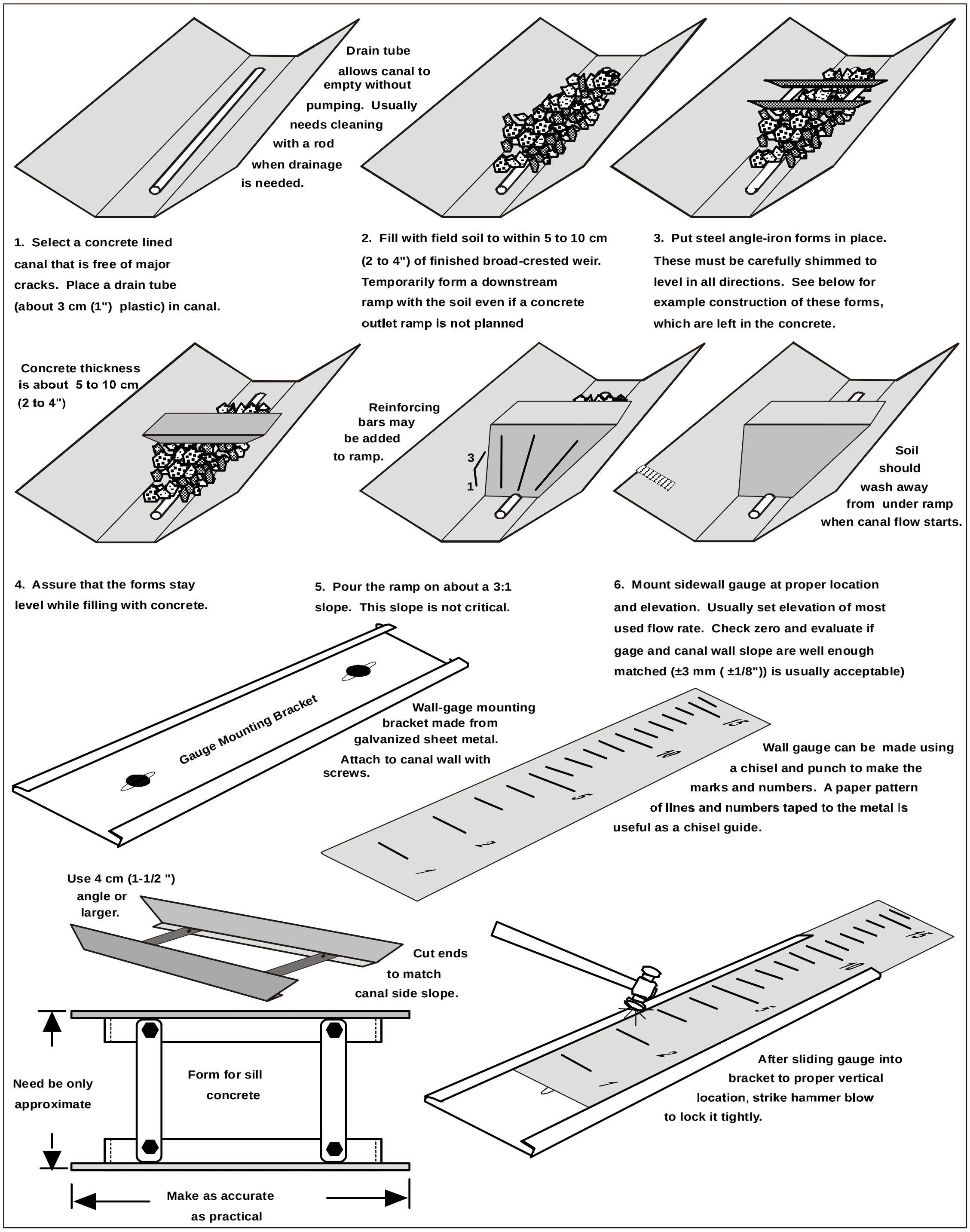


Figure 9. Simple Construction Method for Flumes in Small Farm Canals

Easy-To-Use Scales For Differential-Head Meters The common differential head meters are Venturi meters, orifice meters and Elbow meters. All are used in irrigated agriculture, and each is described in various common handbooks, such as Brater and King (1976). The Venturi meter, Figure 10, constructed from plastic pipe parts is described in detail in Replogle and Wahlin

(1998), and illustrates a simple readout method applicable to differential-head meters, using with a specially marked ruler stick. The Venturi design parameters should be selected to produce readings on the order of 0.3 to 1.5 m, so that the reading is large enough to minimize reading errors and yet small enough that a ladder is not required for the user.

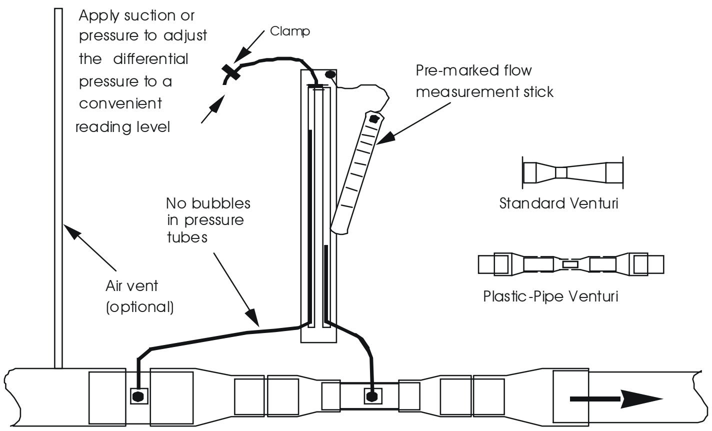


Figure 10. Marked Ruler Can Readily Indicate Direct Discharge Rate

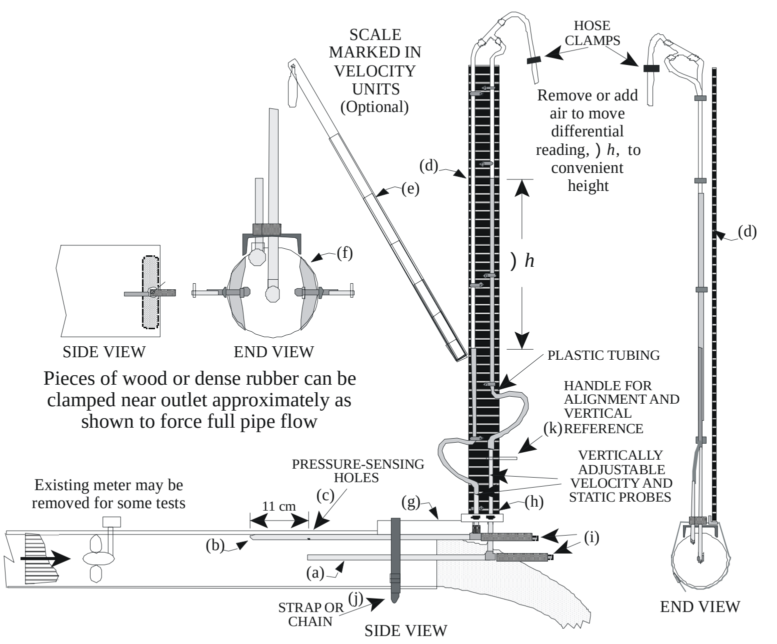


Figure 11. Pitot System for Irrigation Well Measurements

<u>Pitot system for pipe outlets</u> A pitot-tube combined with a static pressure tube can be used to measure discharges from free-discharging irrigation wells. Figure 11 shows the major components. Both the pitot tube (a) and static tube (b) are constructed from standard galvanized pipe of the smallest size available in most local hardware stores (nominal 1/8-inch). The use of the static tube allows the pipe pressure at the plane of the impact pitot to be obtained without drilling a hole in the pipe. The velocity profile is sampled at four points. These selected points

are determined by dividing the circular flow area into two concentric parts of equal area. The velocities at the centers of these two areas are sampled on opposite sides of the pipe and averaged. These four points compare well with the 10-point traverse detailed in Brater and King (1976). Note the pipe center point is not used, because that value is a strong function of the pipe roughness, which can vary widely. If a single point is used in a symmetrical velocity profile, a point on the division line between the concentric halves will produce the most reliable results that can tolerate a large range in pipe roughness. Replogle and Wahlin (2000) describe the system is in more detail.

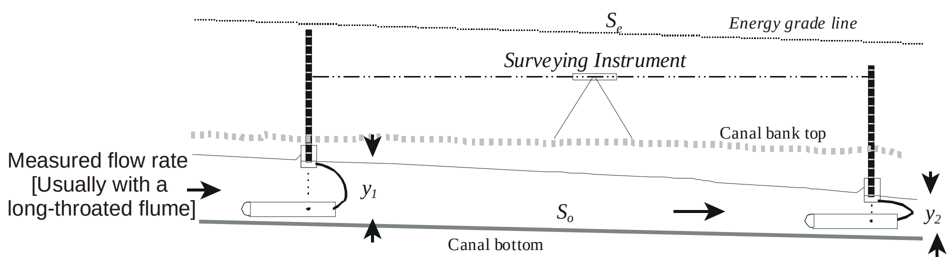


Figure 12. Method for Measuring Head Loss in a Channel

Manning *n* measurement Field measurement of Manning *n* values in prismatic canals can be determined to accuracies limited mostly by the accuracy of the known flow rate. If a long-throated flume is used with the depth detection similar to that shown in Figure 12, then the flow rate can be accurate to within about 2% or 3%. Static pressure tubes like those of Figure 2 are situated as shown in Figure 12 at distances of up to 400 m apart, somewhat depending on the surveying instrument available. By positioning the surveying instrument midway between the static-pressure tube stations, errors in instrument readings are minimized. Small cups are suspended into the surface of the flow and the water levels are read on the stable water levels in the cups with a point gage. The point gage elevations relative to each other are determined using the surveying instrument so that the elevation difference between the two cups can be accurately determined, usually within 1mm. The canal size and shape must also be accurately measured, because the flows in most canals are not uniform, that is, the water surface slope, the energy line slope and the canal slope are not parallel. Thus, a backwater curve computation such as the method in Chow (1959, Table 10.4) can be used to "back out" the Manning n value.

Under-Used Techniques

Stabilizing canal deliveries Often flow through an outlet from a supply canal is introduced into a farm canal where farm operations can vary the backwater levels against the outlet. Thus, the flow through the outlet varies and fluctuates both the farm delivery and the supply canal as in Figure 13a. If field elevations permit, a simple over-fall weir can isolate the supply canal from the farm system so that the farm operations cannot affect the operation of the supply canal. This will require a weir edge height that is at least 50 mm above the highest expected backwater elevation. This will usually require a large Δh, Figure 13b, unless the weir is impractically wide. The situation in Figure 13c uses a long-throated flume to isolate the supply and farm canals by exploiting the large submergence that can be tolerated, and requires a small Δh.

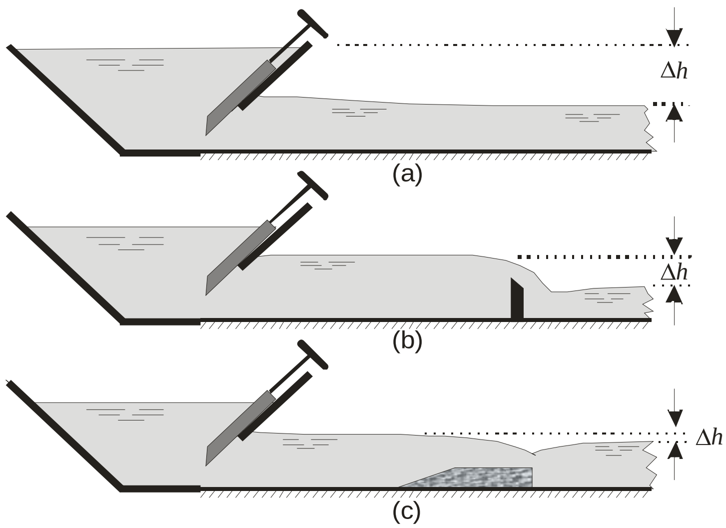


Figure 13. Use of a Flume or Weir to Stabilize Flow from a Main Canal Outlet.

Canal Level Control Long-Crested Weirs of either the "Duckbill" shape or diagonal style, Figure 14, are found to be underused, particularly in the United States. Their design-length versus head-change is adequately predicted using standard weir equations. They can be fitted with "flush-through" gates for periodic sediment management and canal maintenance. They can be combined with underflow gates to reduce the required labor of frequent gate adjustments during canal deliveries (Walker, 1997).

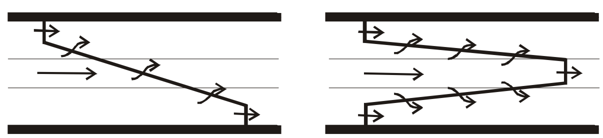


Figure 14. Plan View of Diagonal Weir and Duckbill Weir.

Checking a flow profile Sometimes it is desirable to verify that the approach flow to a channel flume or weir is not distorted to one side. One way to evaluate this is to attach perforated irrigation tubing, available from many sources with holes at about 15 cm and 30 cm spacing, to a heavy chain to hold it tightly to the channel floor and walls (Figure 15). Air is forced into the tube to form a bubble curtain that rises to the surface and makes a visible outline across the channel that is a function of both the channel shape and the velocity profile through which the bubbles pass on their relatively uniform velocity rise from the channel boundary to the surface. In the case of a prismatic channel, a non- symmetrical outline on the surface would indicate a distorted flow profile.

For irregular channel cross-sections, the picture is not so clear because the outline on the surface depends on both the point of bubble origin on the channel boundary and the flow profile. There is, however, a secondary use for the surface outline. The area in square units of measure, say m^2, multiplied by the rise velocity of the bubbles, which is a fairly constant rate of about 0.218 m/s, gives the channel flow rate in m^3/s (Herschy, 1985). A limitation of the method is the inconvenience of determining the area defined by the plane of bubble release and the bubble "froth line" on the surface. This line is fairly distinct, however, because the bubbles tend to break up into the optimum size to rise at the rate stated, thus leaving larger and smaller bubbles to drift downstream in sort of a "beard" effect.

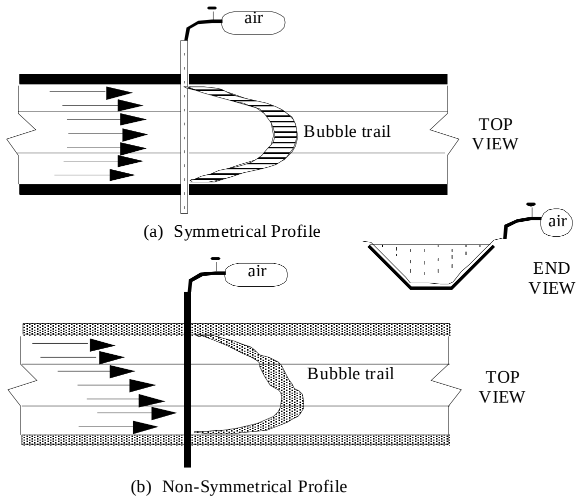


Figure 15. Bubble Curtain Used to check velocity profile.

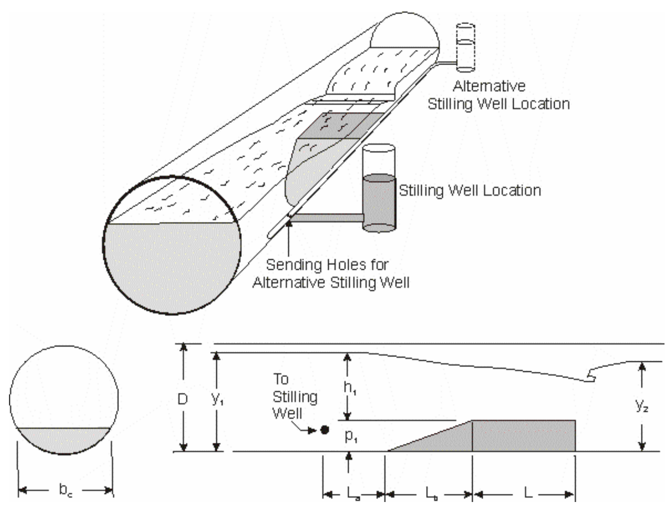


Figure 16. Suggestions for Using a Long-Throated Flume in a Culvert with Alternative Locations for the Stilling Well

<u>Stilling well locations</u> Often overlooked is that the stilling well to a flume or weir can frequently be at a location that is more convenient to service than when placed immediately beside the flume or weir in the cross-channel plane of the depth sending location. This technique, described earlier for portable flumes, can also apply to permanent flumes. Moving the stilling well is particularly useful when field culverts necessary for machinery movement over farm canals are fitted with long-throated flumes. Figure 16 shows a static pressure tube like that of Figure 2 being fastened to the wall of the culvert with the sensing holes at the location of

the upstream depth point. The conduit to the alternative stilling well can pass over the top of the flume if it is small enough to obstruct less than about 1% of the flow area at the lowest flow depth of interest. This would thus avoid digging on the outside of an existing culvert.

For portable flumes in circular pipes and culverts, a convenient method of laying out an ellipse for the ramp portion is illustrated in Figure 17. I was shown this method by a friend many years ago, but have not seen the method described elsewhere.

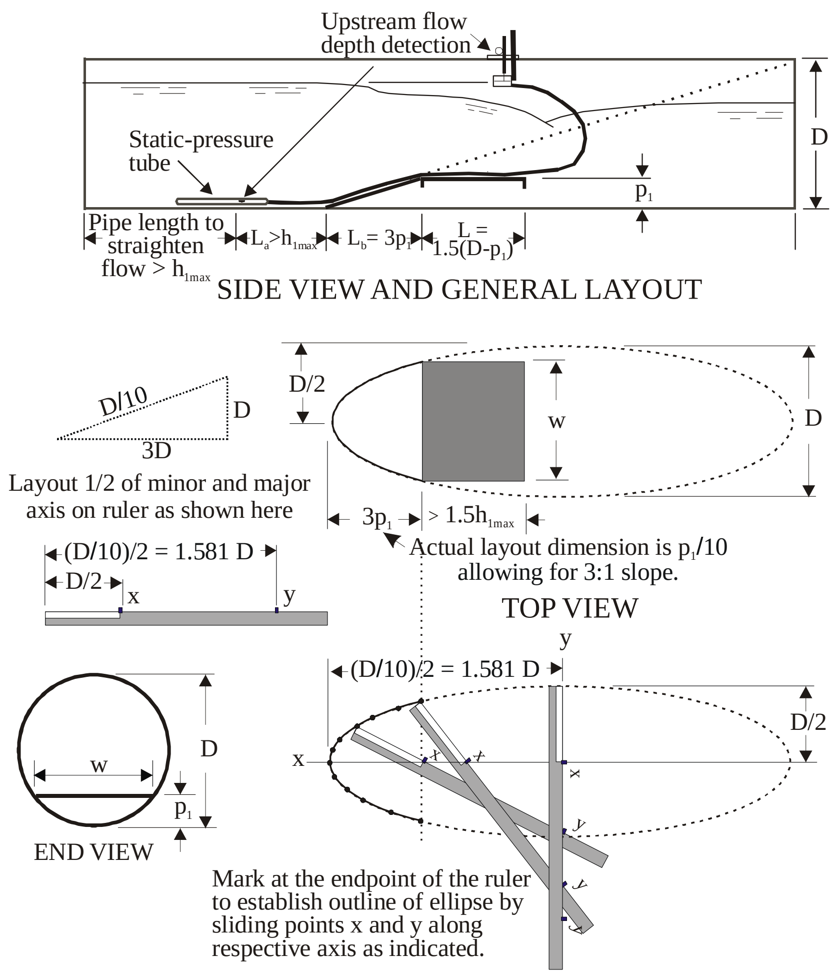


Figure 17. Ellipse Layout for Constructing Portable Flumes to Use in circular Pipes

SUMMARY

Several field techniques to help attain accurate flow measurements along with suggestions for performing convenient field constructions are discussed. Use of these suggestions is intended to make flow control and measurement practical at the field level.

REFERENCES

Bos, M.G. 1989 *Discharge Measurement Structures.* Third Revised Edition, Publication 20. International Institute for Land Reclamation and Improvement/ILRI. P.O. Box 45, 6700 AA Wageningen, The Netherlands. 401 pp.

Bos, M. G., J. A. Replogle, and A. J. Clemmens. 1991. *Flow Measuring Flumes for Open Channel Systems*. American Society of Agricultural Engineers. 321 pp.

Brater, Ernest F., and Horace Williams King. 1976. *Handbook of Hydraulics.* 6th ed. McGraw-Hill Book Co., New York. 604 pp.

Chow, Ven Te. 1959. *Open Channel Hydraulics*. McGraw-Hill Book Company, NY. 680 pp.

Herschy, R.W. 1985. *Streamflow Measurements*. Eleevier Applied Science Publishers, London and New York. 553 pp.

Replogle, J. A. 1997. Practical technologies for irrigation flow control and measurement. Journal of Irrigation and Drainage Systems. Kluwer Academic Publishers, The Netherlands 11(3):241-259.

Replogle, J.A., B.J. Fry, and A.J. Clemmens. 1987. Effects of non-level placement on the accuracy of long-throated flumes. Journ. of Irrigation and Drainage Engineering. ASCE. 113(4):584-594.

Replogle, J. A. and B.T. Wahlin, 2000. Pitot-static tube system to measure discharges from wells. Journal of Hydraulic Eng. 126(5):335-346.

Replogle, J.A. and B.T. Wahlin. 1994. Venturi meter constructions for plastic irrigation pipelines. Appl. Engr. in Agric. 10(1):21-26.

Wahl, T. L., A. J. Clemmens, J. A. Replogle, and M.G. Bos. 2005. Simplified design of flumes and weirs. Irrigation and Drainage 54:231-247.

Walker, Robert E. 1987. Long crested weirs. In: D. D. Zimbelman (ed.) *Planning, Operation, Rehabilitation and Automation of Irrigation Water Delivery Systems*. Proc. Symp., ASCE, Portland, OR. 28-30 Jul. 1987. pp. 110-120.

Wahlin, B.T., A.J. Clemmens, and J A Replogle.. 2000. Evaluating the measurement accuracy of surface water flows and accumulated volumes. *published:* CD Rom unpaginated. Proc. International Conference on Water Resources Engineering. ASCE. Joint Conference on Water Resources Planning and Management. Minneapolis, MN, July 30-August 2.

LINEAR ANIONIC PAM AS A CANAL WATER SEEPAGE REDUCING TECHNOLOGY

Delbert M. Smith[1]
Chad Martin[2]
Rick Susfalk[3]
Timothy Gates[4]

ABSTRACT

Reclamation has been collaborating with the Desert Research Institute and Colorado State University to better understand the use of linear anionic polyacrylamide (PAM) to reduce canal seepage. The project has been divided into four main areas – laboratory experiments, quasi-field scale experiments, full-scale canal applications, and environment/human risk characterization. An independent peer review panel of experts has convened several times to provide guidance on the research that is being done for the field and laboratory studies as well as the risk characterization report. A final Risk Characterization Report will be completed in 2007 and will provide water managers with guidance on the use of dry PAM formulations and to what extent PAM is an environmentally acceptable technology. Most of the field experiments will be completed by the end of Water year 2007. If it is determined that PAM applications to canals is environmentally acceptable, guidance will be developed on how best to responsibly apply PAM and what field conditions are most favorable.

During Water Year 2005 a series of 30 very controlled experiments were run in a 160-foot long test trough along with some quasi-field scale experiments, to gain an understanding on how and to what extent various application rates of PAM reduced canal seepage. Data from these experiments were used in Water Year 2006 to design and carry-out full scale canal applications on six canals. The main focus of this paper will be on seepage results from applications on three canals in southeast Colorado.

INTRODUCTION AND BACKGROUND

There is increasing interest among water user organizations, State and Federal agencies, and the public in using irrigation water more efficiently. On a majority of irrigated lands in the western U.S., more efficient water use could be achieved. The continuing increase of water requirements for municipalities and industry, fish, wildlife and habitat, and recreation is closing the gap between available water supply and demand. In addition to reducing water available to others, inefficient conveyance and excessive application of water for irrigation often causes local drainage problems and may result in excess return flow which add to downstream salinity on some Western rivers.

---

[1] Hydraulic Engineer, Bureau of Reclamation, Water Resources Planning and Operations Support Group, Denver, CO
[2] Graduate Student, Civil Engineering, Colorado State University, Fort Collins, CO
[3] Assistant Research Scientist, Desert Research Institute, Division of Hydrologic Sciences
[4] Professor, Colorado State University, Department of Civil and Environmental Engineering

Past comprehensive studies of water conservation opportunities carried out by the Bureau of Reclamation (Reclamation) and the Bureau of Indian Affairs (1) concluded that overall average irrigation system efficiency, resulting in reduced diversions, could be improved by appropriate implementation of off-farm and on-farm water conservation measures. Improvement of conveyance systems appears to have potential for improving efficient use of water. From the table below, the studies concluded about **two-thirds** of the improvement would result from better management and improvement in the water conveyance (off-farm) system.

Seepage reduction by lining and/or piping canals and laterals (off-farm facilities) accounts for over one-third of the reduced diversions. Seepage losses, caused principally by pervious soils in which canals and laterals are constructed, offer the greatest opportunity for increased water delivery efficiency.

Table 1. Project Management and Facilities to Point of Farm Delivery

Type of Conservation Measure	Reduced Diversion
Improved water management	10 percent
Automation and improved control measures	7 percent
Seepage reduction (canal lining and pipe)	37 percent
Recycling of return flow	11 percent
Other	1 percent
Total conveyance system	66 percent

(Table reproduced from "Report on the Water Conservation Opportunities Study", Department of the Interior, Bureau of Reclamation and Bureau of Indian Affairs, September 1978).

References

(1) Report on the Water Conservation Opportunities Study, Department of the Interior, Bureau of Reclamation and Bureau of Indian Affairs, September 1978.

(2) Irrigation Water Use and Management, Interagency Task Force Report, Department of the Interior, Department of Agriculture, Environmental Protection Agency, June 1979.

POLYACRYLAMIDE (PAM)

PAM has been used for more than 10 years in furrow-irrigation to control soil erosion. Experiments of using PAM to reduce canal seepage started in 1999 by the Reclamation and the Uncompaghre Valley Water Users Association. They set up a wooden trough and began running experiments with porous soils and various application rates of PAM. Experiments of using PAM as a canal seepage control technology expanded from 2000 to 2004 into several small canals in western Colorado and it became important for Reclamation to have a better understanding of the risks and benefits of this new technology.

When added to canal water, linear, anionic PAM, a long-chain synthetic polymer flocculates and drops suspended sediments out of suspension. This creates a lower hydraulic conductivity layer along the canal perimeter that can reduce seepage losses. PAM is potentially an attractive alternative for seepage control since it is relatively easy to apply and is inexpensive compared to conventional channel lining materials. Its flexibility of application also provides the potential to create seepage reduction schedules and to selectively control seepage quantities in response to changing economic and hydrologic conditions. PAM application to canals in the Arkansas River Valley was field tested on reaches of the Catlin Canal, Lamar Canal, and Rocky Ford Highline Canal in the summer and fall 2006. Seepage estimates were made using a mass balance procedure that employed flow measurements with acoustic Doppler current profilers (ADCP) and/or acoustic Doppler velocimeters (ADV) along with other measurements. Water samples were collected during the field test and analyzed for PAM and for the acrylamide monomer, which is the compound from which PAM is created. Objectives included an evaluation of the effectiveness of PAM in seepage reduction as well as an assessment of possible environmental and health risks from the application.

Preliminary Findings on Seepage Reduction

In the summer of 2006, four PAM applications were completed in Arkansas River Valley irrigation canals. Study reaches were chosen on three different canals to capture variability in water and channel properties. By studying canals that differ from one another, the conditions that maximize the effectiveness of PAM should be easier to identify. The conditions within the studied canal reaches are summarized in Table 2. Further analysis, including assessment of measurement error, will be conducted in the future to refine these results. The polyacrylamide product used in all canal applications contained a 92% active ingredient. The active ingredient of PAM varies among manufacturers, so the application rates shown in Table 1 reflect active quantities.

Table 2. Summary of Preliminary Findings on Use of PAM for Seepage Reduction, Summer 2006

Canal	Test Length	Average Pre-PAM Seepage		PAM Application Rate		Average Canal Flow Rate within First Month	Average Seepage Reduction within
	(mile)	(cfs/acre)	(cfs/mile)	(lbs/acre)	(lbs/mile)	of Application	First Month of Application
Catlin	2.7	0.90	2.5	17.9	50.6	111 cfs	87%
Lamar	5.8	0.90	2.0	11.6	28.1	48 cfs	38%
RF Highline #1	19.9	0.20	0.7	12.3	46.8	144 cfs	0%
RF Highline #2	2.5	0.70	3.4	13.0	63.3	124 cfs	59%

The first application was conducted in early June on the Catlin Canal south of Rocky Ford (Figure 1). The study reach extended 2.7 miles from the upstream site 201 to the downstream site 202. Granular PAM was applied dry to the water from a motorized boat using two handheld spreaders. Each handheld spreader was filled with a pre-weighed amount of PAM, which was then applied by two people within the boat while traveling in the upstream direction over 0.10-mile increments so that the rate of application could be measured and maintained. As seen in Table 1, this first experiment resulted in the greatest impact among tests in 2006, as seepage was reduced by about 87% within the first month after PAM application. This large reduction may have resulted from water chemistry that favored PAM-suspended sediment flocculation, an application rate that was greater than that used on the other canals, and from the possible presence of finer-grained sediments within the canal water. Follow-up seepage loss measurements were continued through November (5 months after PAM application) so that the effect of PAM over time could be observed. The longevity of the PAM influence will be discussed later in the report.

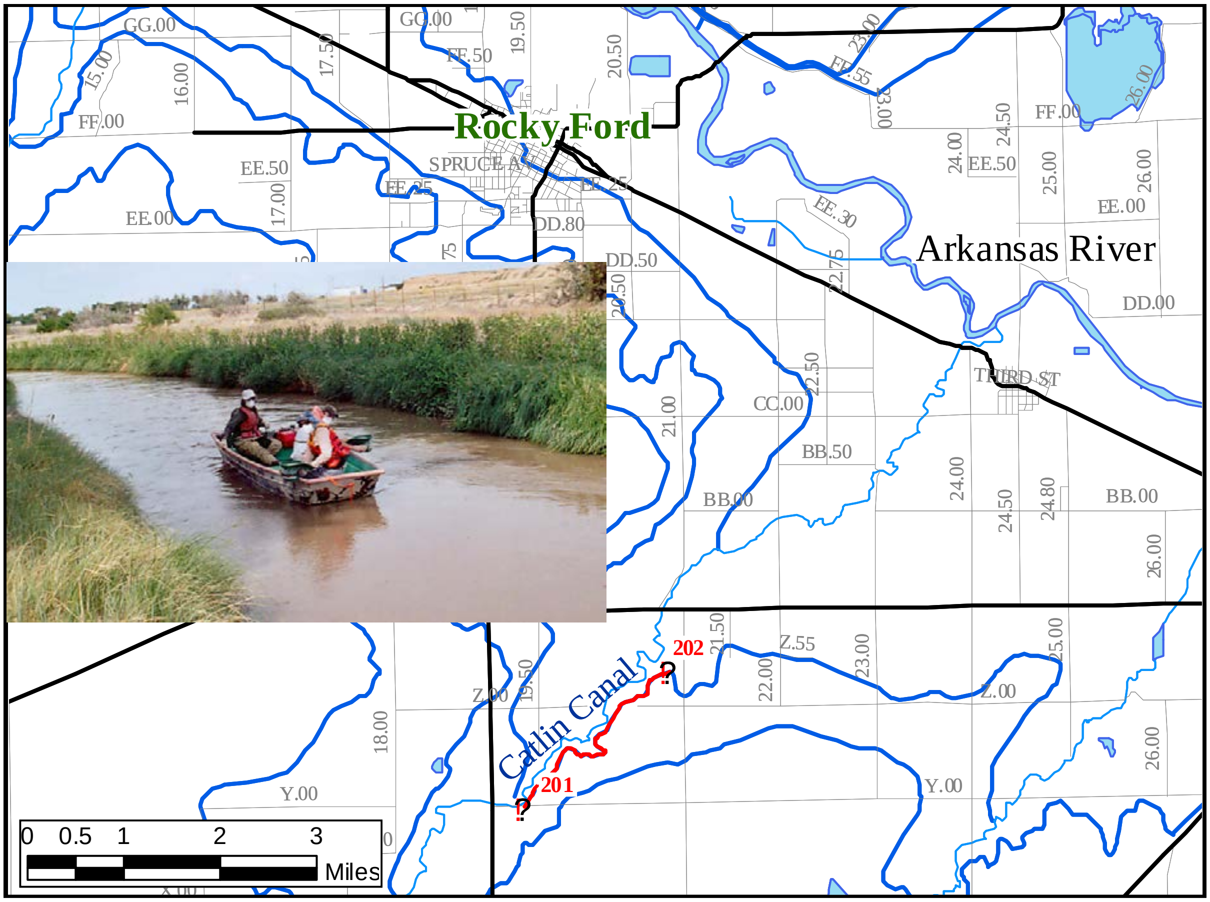


Figure 1. PAM Application Study Reach on the Catlin Canal in Summer 2006.

The second PAM application in 2006 was conducted on a reach of the Lamar Canal. The 7.4-mile study reach was located between Lamar and Granada just south of Colorado Highway 50, extending from site 400 to site 405 (Figure 2). PAM was applied to the entire study reach; however, due to irrigation diversions from the canal, all post-application measurements were taken over a 5.8-mile canal segment between sites 401 and 405. Therefore, all results reported herein apply to the reach between the upstream site 401 and the downstream site 405. The application technique was similar to that of the Catlin Canal application, as a motorized boat and two handheld spreaders were used. A picture of this application technique appears in Figure 2. As seen in Table 2, the PAM application on the Lamar Canal is estimated to have reduced seepage losses by an average of about 38% within the first month after application. It is thought that if sediment levels within the Lamar Canal had been higher during the application process, seepage reduction would have likely been greater.

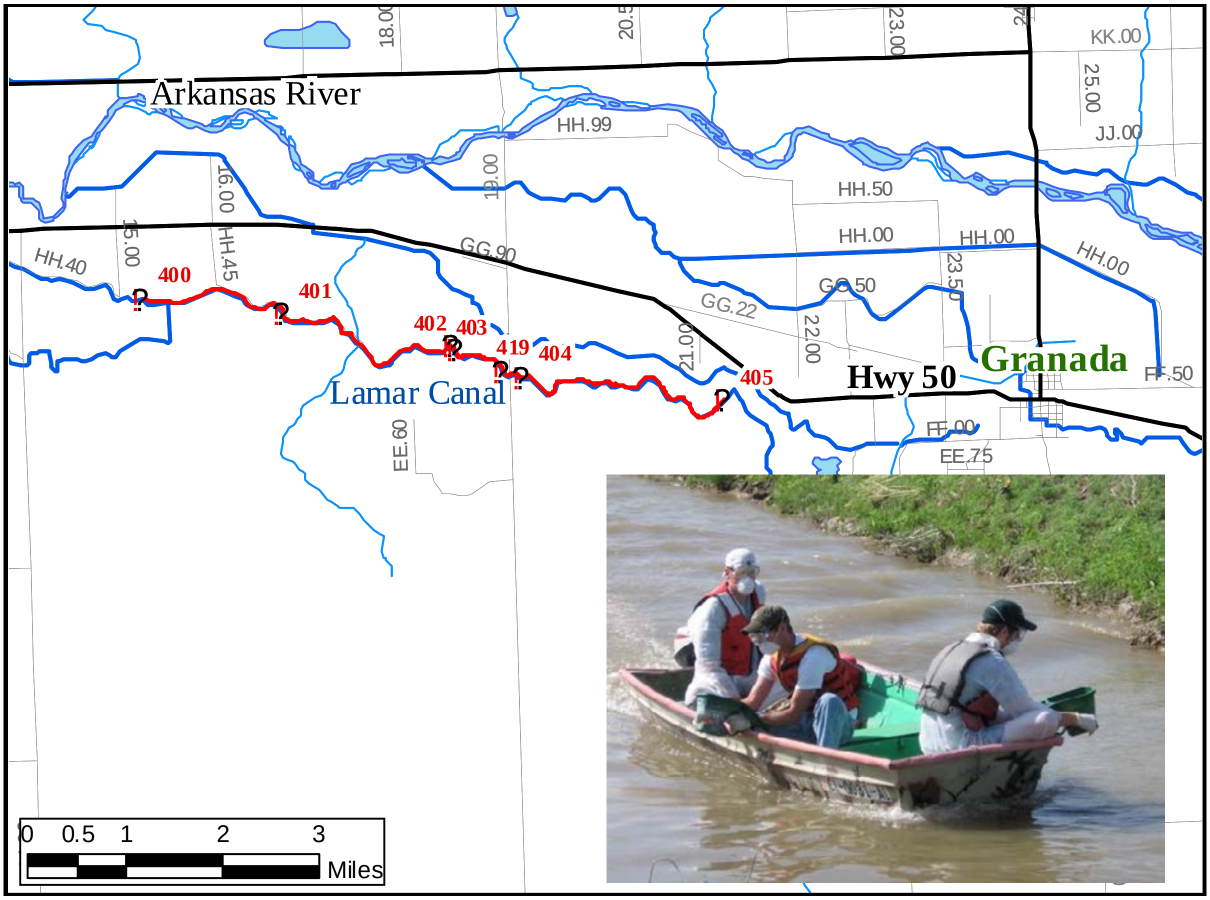


Figure 2**.** PAM Application Study Reach on the Lamar Canal in Summer 2006.

Two PAM applications were completed on the Rocky Ford Highline Canal. The first application stretched 19.9 miles from the upstream site 201 to the downstream site HH-4.27 (Figure 3). The canal segment between sites 200 and 201 was used as a control reach so that the canal's conditions could be observed without the presence of PAM. This is the longest length of canal to which PAM was applied in 2006; accordingly, the application process took two days to complete. For this test, PAM was applied using an automatic battery-powered spreader that was mounted on a small boat. The spreader's hopper was filled with a pre-measured amount of PAM then emptied while moving in the upstream direction over an incremental length of canal so that the application rate could be maintained. A photograph of this technique and the automatic spreader appears in Figure 3. The first PAM application to the Rocky Ford Highline Canal was not as successful in reducing seepage. Multiple factors could be used to explain the ineffectiveness of this application, including the application method, water chemistry, and a variety of canal conditions. From pre-PAM and post-PAM seepage measurements, the stretch of canal between sites 201 and 202/301 displayed the greatest amount of seepage. Since post-PAM measurements revealed no seepage reduction in this section of canal, it was the chosen study reach for a second PAM application, which took place following a storm event that created high sediment levels in the canal. For the second application, granular PAM was applied to the 2.5-mile canal segment between sites 201 and 202/301. PAM application also included a segment extending a distance of 1.5 miles upstream of site 201 to ensure adequate hydration of PAM and sediment flocculation prior to reaching site 201. As seen in Table 1, the second PAM application resulted in average seepage reduction within the first month of about 59%. It seems that the higher sediment concentration present in the canal water during the second application resulted in more sediment and PAM settling to the canal bottom, which more effectively lined the channel bed and reduced seepage to a greater extent.

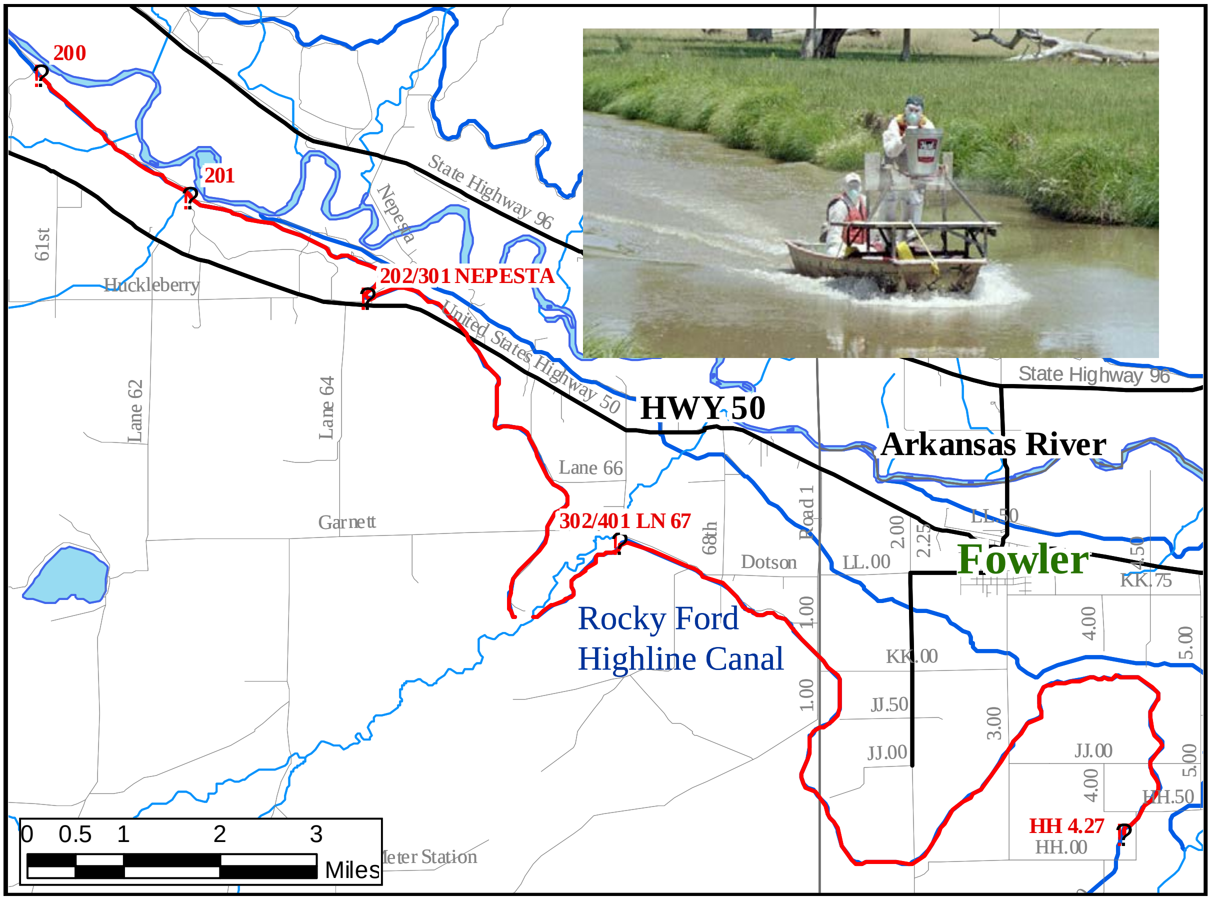


Figure 3. PAM Application Study Reach on the Rocky Ford Highline Canal in Summer 2006.

Follow-up seepage measurements were conducted throughout the 2006 water season to assess the effectiveness of PAM in sustaining canal seepage reduction over time. Based upon data collected in 2006 on the Catlin, Lamar, and Rocky Ford Highline canals, it appears that PAM continued to be relatively effective within three to four months after application. Data suggest a slight drop in seepage reduction by about 10 percentage points.

Seven post-PAM application seepage measurements were conducted over a span of 152 days on the Catlin Canal. The results show a minor drop in seepage reduction towards the end of the water year; however, the effectiveness of the PAM application was still substantial (Figure 4).

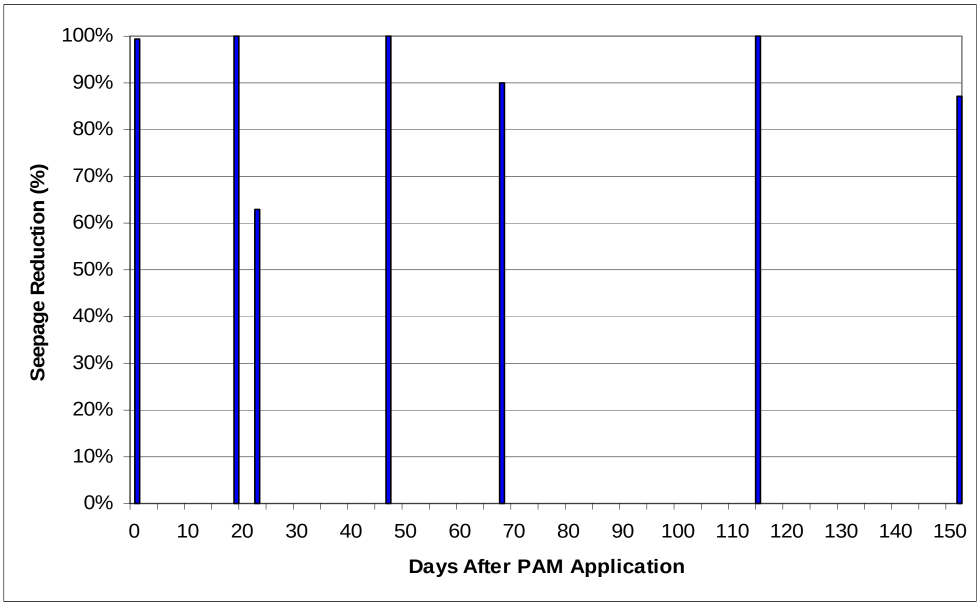


Figure 4. Plot of Estimated Seepage Reduction in the Catlin Canal after PAM Application.

Four seepage measurements were conducted on the Lamar Canal over a 113-day period following the PAM application. PAM effectiveness appeared to have respectable longevity. The Lamar Canal showed results similar to the Catlin Canal, as seepage reduction declined slightly in the months following PAM application (Figure 5).

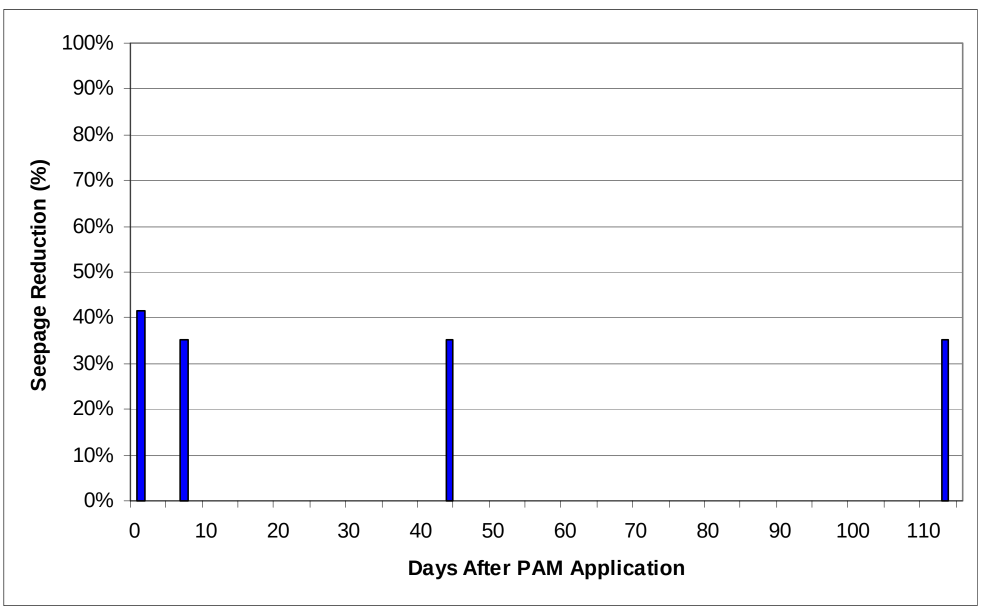


Figure 5. Plot of Estimated Seepage Reduction in the Lamar Canal after PAM Application.

In the 105 days after the second PAM application to the Rocky Ford Highline Canal, five seepage measurements were completed (Figure 6). With respect to longevity, the second PAM application on the Rocky Ford Highline Canal revealed results similar to those for the Catlin and

Lamar canals. Canal seepage reduction was the greatest in the first few days following the application then it began to reduce by approximately 10 percentage points over the following months.

Overall, preliminary results suggest that longevity is considerable, since reduction in estimated water loss from canals remained fairly stable in the weeks and months following an application. Continued research will be conducted to test the frequency of PAM application required to sustain significant seepage reduction in irrigation canals under a variety of representative conditions. It is quite possible that the necessary number of applications will vary from irrigation season to irrigation season, depending upon water, channel, and ground water characteristics.

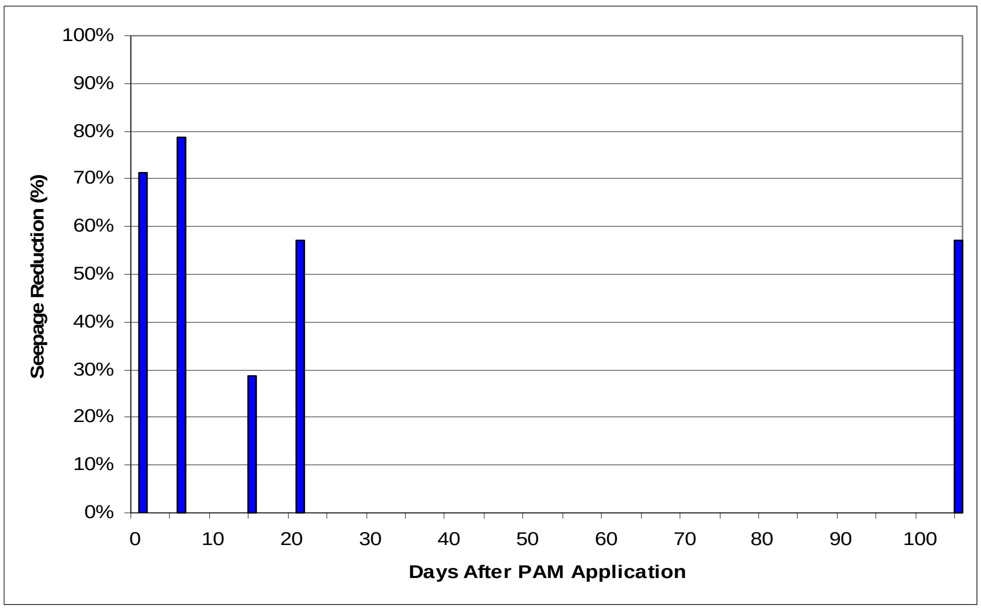


Figure 6. Plot of Estimated Seepage Reduction in the Rocky Ford Highline Canal after PAM Application.

Preliminary Assessment of Environmental and Health Risks

The concentration of PAM found in the water column after application peaked at 2 to 4 times that of the EPA Drinking Water Standard of 1 part per million (ppm). However, these elevated concentrations were short-term, lasting during PAM application and up to 5 hours after completing the application of PAM. Concentrations then remained below the drinking water standard. A soon-to-be-released report on environmental and health risks from PAM application and the release of the acrylamide monomer showed that the concentrations measured in the canal water would pose little to no risk to humans, especially given that the concentrations were elevated for a very short period of time.

Expected Impact of On-Going Research

Investigations will continue over the next couple of years to better understand the impact of method, rate and frequency of PAM application; suspended sediment concentration; water salinity and temperature; soil texture in the canal perimeter; adjacent groundwater elevation; and other factors on the effectiveness and economy of PAM for controlling seepage.

PAM can potentially have significant economic impacts due to inexpensive application costs and a number of benefits that can be derived from reduced canal seepage. It is currently estimated that PAM application will cost $122 to $327 (2006 dollars) per mile along a canal per year, which is less than about 3% the cost of conventional lining methods. The application cost does not include the price of equipment; however, preliminary estimates suggest a boat, motor, and spreader can be purchased for an approximate total of $2,000 - $3,500 and protective gear costs $20 per application per person. It is believed that a portion (perhaps 10 to 20%) of the saved seepage water may be able to be salvaged and converted to beneficial crop consumptive use. This salvaged water would be derived from the likely reduction in upflux to non-beneficial evapotranspiration from high water tables which are partially caused by seepage. According to the Arkansas River Compact, all remaining seepage must be allowed to return to the river. Reduction in canal seepage likely will lead to a lowering of the saline shallow water table in the Valley, contributing not only to reduced non-beneficial water use but also to a decrease in waterlogging and salinity with a consequent increase in crop production. Furthermore, reduced canal seepage would enhance river water quality by lessening subsurface flows and the associated dissolution and mobilization of salt and selenium loads that move to the river.

Experiments are planned to continue into the 2007 irrigation water year in the Catlin, Lamar, Rocky Ford Highline, and other Arkansas River Valley canals. It is hoped that the most beneficial ways for canal companies to use PAM in reducing canal seepage can be discovered and implemented.

IN-SITU NON-DESTRUCTIVE MONITORING OF WATER FLOW IN DAMAGED AGRICULTURAL PIPELINE BY AE

Tetsuya Suzuki[1]
Masayasu Ohtsu[2]
Masao Aoki[3]
Riota Nakamura[4]

ABSTRACT

Deterioration of water-flow function in a pipeline system has resulted from water-leak accidents due to damage accumulation in pipe materials. The repaired pipeline system cannot be evaluated of water-leak phenomena under the inner water pressure condition. Non destructive evaluation of water-flow function in pipeline system is currently in urgent demand. In this study, acoustic emission (AE) method is applied to the evaluation of water-flow function in an existing agricultural pipeline, which was inspected and then repaired after water-leak accidents. At three conditions, experiments were conducted. First, a water leak phenomenon which the pipeline filled full with water was investigated. Secondly, an evaluation process of water-drained from full to empty condition was made in the pipeline. Thirdly, experiments were carried out condition of the pipeline was filled with water after repairing the water-leak section. AE method was applied to detecting signals of water-leak and flow under these conditions. The results show that water-leak in the pipeline system could be quantitatively evaluated by using such AE parameters, such as generation behavior and AE energy. In the third condition, AE generation behavior was varied with the situation of the pipeline until the pipeline was filled with water. AE energy showed the same tendency as AE generation behavior. When an AE sensor was installed on an air valve, AE energy dropped temporarily as the pipeline was being filled with water. However, when water was filled up to the air valve, the increase in AE energy was confirmed. Thus, it becomes clear that when a pipeline is being filled with water after the repair, the situation of water in the pipeline can be clearly identified through AE monitoring. Discharge evaluation of a damaged pipeline system can be conducted in a short time through AE monitoring.

INTRODUCTION AND RESEARCH BACKGROUND

When planning a water pipeline system, the size of a facility and a structural system are determined only from the results of hydraulic analysis. In existing pipeline systems, however, water leakage accidents have been reported in the deteriorated sections of the system due to the cumulative damage of pipeline materials (Nawa et al, 2002). The measures taken by pipeline administrators are mainly winding-up treatments on-site after leakage has been recognized. As a

[1]Research Associate; Nihon University; 1866, Kameino, Fujisawa, Kanagawa, Japan; t.suzuki@brs.nihon-u.ac.jp
[2]Professor, Kumamoto University, 2-39-1 Kurokami, Kumamoto, Japan; ohtsu@gpo.kumamoto-u.ac.jp
[3]Associate Professor; Nihon University; 1866, Kameino, Fujisawa, Kanagawa, Japan; m--aoki@brs.nihon.ac.jp
[4]Professor, Nihon University; 1866, Kameino, Fujisawa, Kanagawa, Japan; rio-nakam@nifty.ne.jp

result, recently the unsafe sections have been expected to exist in the pipe system from statistical analysis using leak accident data. For maintenance and management in existing structures, non-destructive testing (NDT) methods need to be developed, because pipeline systems are installed underground and the damage can not be checked visually in service. In recent work, it was reported that elastic wave method (e.g. acoustic emission) is effective for leak detection in pipeline system (Vahaviolos et.al, 2001; Kamiya et al. 2002). The acoustic emission (AE) method is passive technique for detection of elastic wave from existing structures.

In this study, the NDT techniques are developed in water pipeline systems using acoustic emission (AE) method, which detects elastic waves passively (Suzuki et al, 2004). This paper reports 3 results of quantitative evaluation of AE measurements in an existing agricultural pipeline.

NON-DESTRUCTIVE MONITORING OF PIPELINE SYSTEMS BY ACOUSTIC EMISSION METHOD

Propagation and measurements of elastic waves

There are basically two types of hydraulic conditions in pipeline systems; a stationary state, and a non-stationary state, depending on whether the water flow velocity and water pressure change with time or not. A non-destructive evaluation method had been developed previously, focusing on water-leakage phenomena. High-accuracy non-destructive monitoring requires a quantitative evaluation of both the stationary and non-stationary states of the water flow. In the measurements of water pipeline systems by the AE method, elastic waves emitted from the structure are

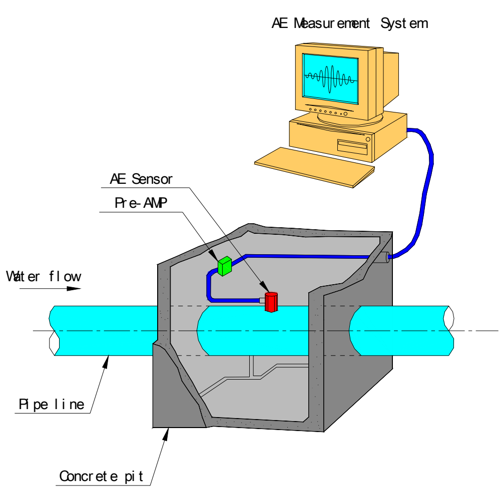


Figure 1. AE measurement system in pipeline

Photograph 1. Monitoring outline

detected passively by AE sensors, as shown in Figure 1 and Photo 1. These evaluation is conducted for the elastic waves detected by AE sensors which are attached to the pipe surface.

Properties of detected AE wave

The elastic waves transmitted from water in pipelines have different properties depending on the hydraulic conditions inside the pipeline. The elastic waves change the component properties, depending on the scale of the phenomena and monitoring conditions in the propagation process. An example of a water-leak wave, measured at a point 40 m away from the leakage point when

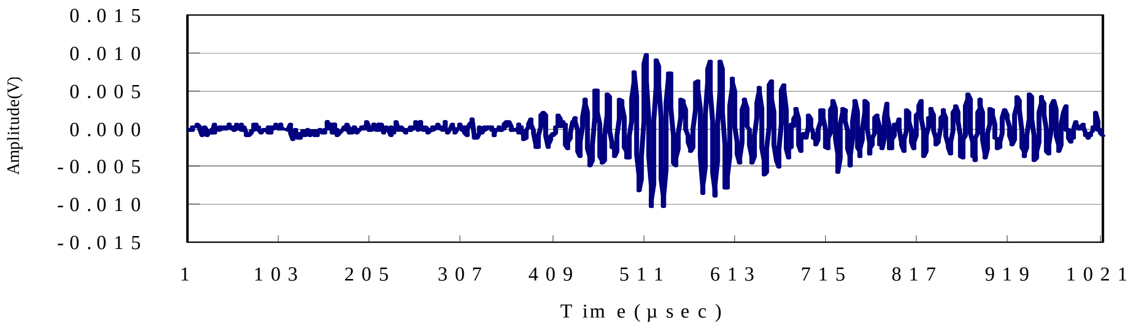


Figure 2. Leak wave detected from an existing pipeline
(V=0.0m/s, Leak point: about 40m away from monitoring site)

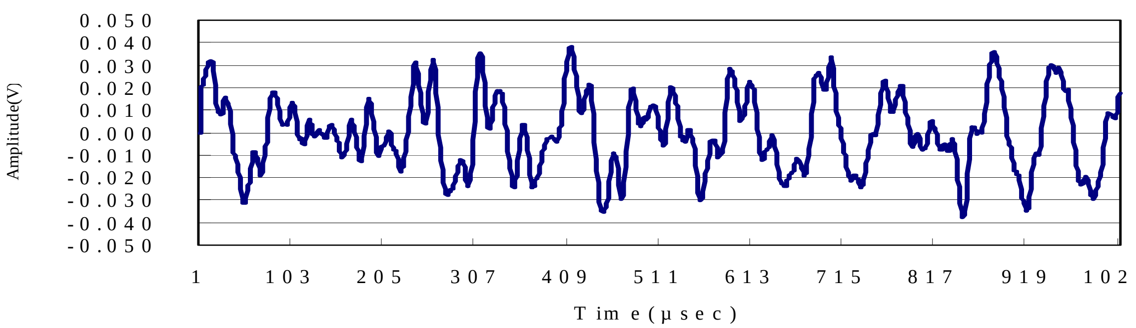


Figure 3. Leak wave detected from an existing pipeline
(V=1.5m/s, Leak point: about 50cm from monitoring site)

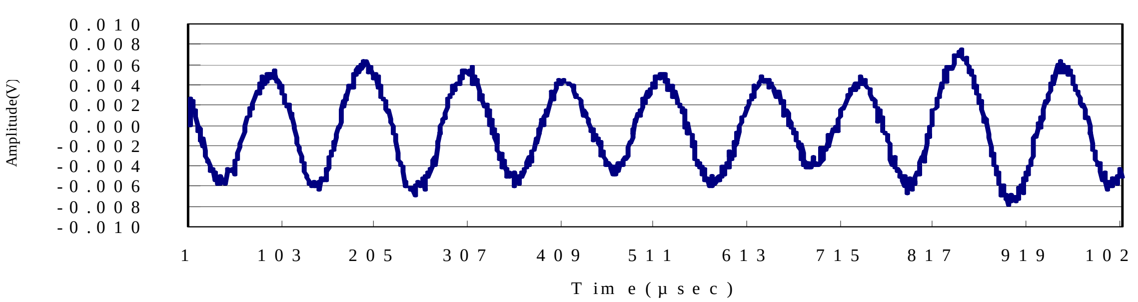


Figure 4. Water flow wave detected under inner water pressure conditions

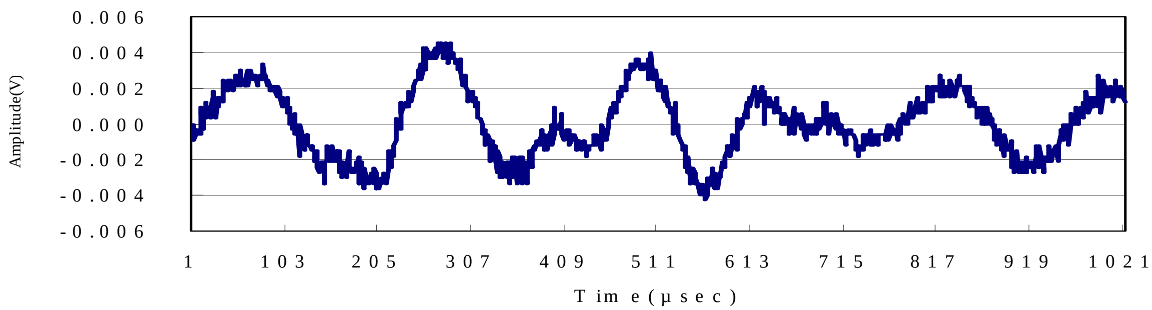


Figure 5. Water flow wave detected in pipeline that has water surface

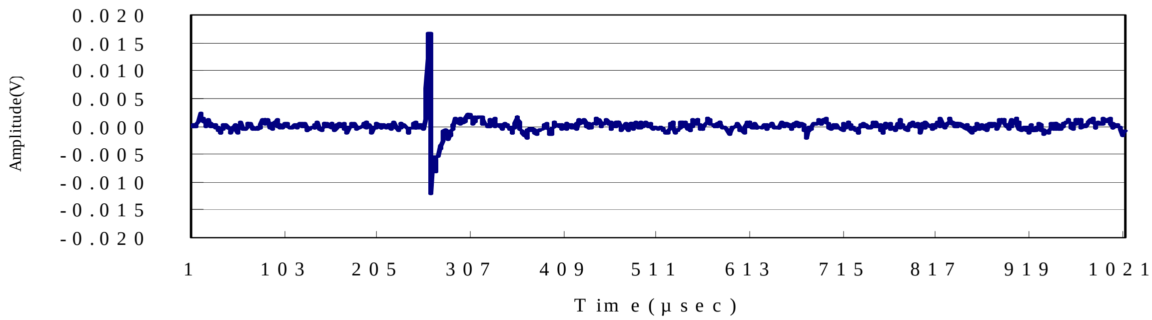


Figure 6. Environmental noise (traffic noise)

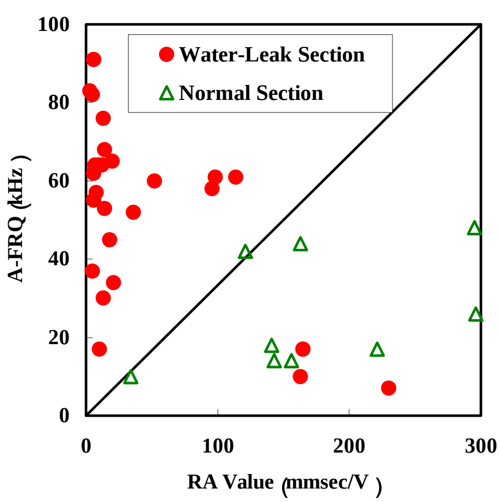


Figure 7. Relations between RA value and A-FRQ

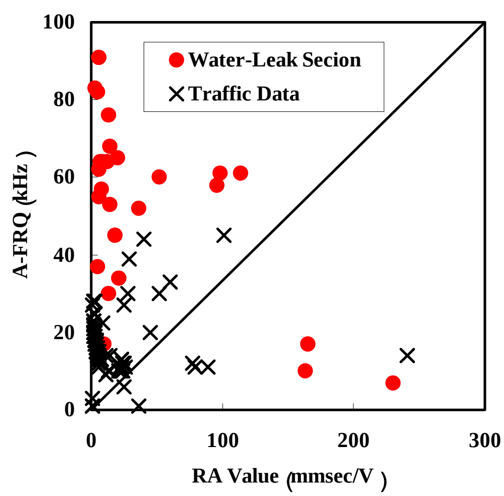


Figure 8. Relations between RA value and A-FRQ (Traffic noise)

water flow was stopped, is shown in Figure 2. Compared with the water-leak wave in Figure 2, the water-leak wave measured near the leakage point when water was flowing, exhibited properties of an irregular continuous wave, as shown in Figure 3. A comparison of Figures. 2 and 3 shows that the wave measured at a point farther from the leakage point in Figure 2 had a higher frequency than the wave measured at a near point in Figure 3. This difference may have been caused by differences in hydraulic conditions inside the pipeline. The elastic wave was shown in Figure 3, a composite wave of those in Figs. 2 and 4. The composite wave has a stronger effect from an elastic wave when water is flowing than from a water-leak wave. Therefore, to detect leakage under normal management conditions, there must be a thorough understanding of the hydrological conditions inside the pipes. Evaluating the characteristics of detection waves using AE parameters, it is possible to conduct a quantitative evaluation. For example, AE rate process analysis, and the analyses focusing on the relation between RA values and average frequency and the relationship between energy and AE generation behavior have been found to be effective for detecting leakage (Suzuki et al. 2004, Suzuki et al. 2005). In cases where the AE method is applied to discharging tests or verification of repair works to pipeline systems, continuous waves with low regularity can be detected when water is filled at the stage where there is a free water surface, as shown in Figure 5. After that, when the water has been filled, continuous waves having regularity can be detected, as shown in Figure 4. If water leakage occurs at that time, the water-leak wave shown in Figure 3 (not Figure 4) will be detected. In this series of investigations, analyses focusing on the relationship between energy and AE generation behavior were found to be effective. In monitoring with the elastic wave method, it is difficult to distinguish environmental noise from the object being measured. Very often buried pipeline systems are located under roadways. The source of environmental noise is automobile traffic. Detection waves taken from existing pipes while automobiles were passing are shown in Figure 6. As shown in Figures. 2-5, there were distinct differences between elastic waves that were detected while water was flowing or leaking and environmental noise. The above findings indicate that setting proper monitoring conditions enables the AE method to be used to detect elastic waves that occur inside pipes under various hydrological conditions even when there is environmental noise. In elastic wave method, it is effective to quantitatively evaluate the properties of detection waves; AE parameters are considered to be particularly effective.

Improving the S/N ratio by eliminating environmental noise

In non-destructive monitoring, environmental noise is usually a problem. Environmental noise with pipeline facilities is usually vibrations from passing vehicles or trains. There is also electromagnetic noise that originates from nearby high voltage power lines. One way to effectively eliminate such noise is to process mathematically the features of measured waves. AE behavior of a pipeline with water flow or leakage was associated with inner water pressure. Noise reduction was used to AE parameters of RA value (rise time/peak amplitude) and the average frequency (AE ring down count/duration).

In this study, an existing pipeline system is examined, applying AE method. AE monitoring was conducted at Kasanohara main channel located in Kanoya, Kagoshima, Japan. The pipeline system was constructed 36 years ago. Water leak accidents occurred 92 times (2.6 leaks per year on average) from 1967 to 2002. 70% of water leaks occurred at joint sections.Inner water pressure was measured as 0.44 MPa under normal operation. AE monitoring was conducted after a gate valve had been closed. The inner water pressure dropped by 23% in 30 minutes, from 0.44 MPa to 0.34 MPa.

AE generating behavior of the leaked section was compared with that of the traffic noise in terms of RA value and the average frequency (JSCM 2003). Results are shown in Figure 7 and 8. Frequencies of traffic noise were lower than 20 kHz. Water leak phenomena were higher than 30 kHz. There is a clear difference between Water-leak and Noise due to traffic. The improvement of S/N ratio that used AE parameter was possible according to relationship RA value and average frequency. Therefore, for the reduction of environmental noise of AE monitoring in pipeline system, AE parameter analysis is effective.

EFFECT OF ELASTIC WAVE PROPAGATION PROPERTIES ON MONITORING ACCURACY

Effects of distance decay and soil conditions

During the propagation process, elastic waves show noticeable energy decay due to the properties of the propagating material or reflection. The most basic factor for defining the properties of elastic wave energy decay is the distance decay. Considering the internal attenuation of the propagating medium, the amplitude u at a distance r from the vibration source can be analytically derived as Eq. (1) below:

$$u = u_0 e^{-\lambda r} r^{-n} \qquad (1)$$

In the model water leakage test, the amplitude of the detected AE wave was an average 60dB at a defective part of 2.0mm, and there were few discrepancies caused by internal water pressure. The water leakage was simulated under the following measurement conditions: water pressure inside SGP20A (20mm diameter) pipes of 0.3 to 0.8MPa, with four types of model defects (0.3, 0.5, 1.0 and 2.0mm). When water leakage is detected from a roadway by ear, a 10Hz wave is propagated 2m with the amplitude decrease by about half, assuming an attenuation ratio of 0.05 and an elastic wave velocity of 500m/s in the soil. The effect of distance decay increases as the frequency band of the water-leak wave increases. At a frequency of 20kHz (at which water leakage is detectable by the human ear), when the wave amplitude is 60dB near the defective part, attenuation results in a detected wave amplitude of 2.4dB, 96% decay at a point 2.0m from the leakage point. This makes it nearly impossible to detect from the ground surface. The peak frequency band of water leakage phenomena reported in previous studies was 10 to 50Hz, and about 50% of the amplitude had attenuated at a point 2.0m from the leakage point. From the results, and given the attenuation properties of waves in the soil, it is clearly problematic to try to detect water leakage by detecting waves in the soil. In pipelines under roadways, water-leak waves propagate through materials having different densities in asphalt, roadbeds, sub grade, etc. Therefore, wave reflection and transmission coefficients of materials greatly affect the measurement accuracy.

Effect of pipe materials on monitoring accuracy

Pipes are made of various types of structural materials, depending on what they will be transporting, the internal water pressure and the environment they will be buried in among other factors. For AE measurements, AE sensors are installed on the pipe material surface to detect elastic waves emitting from the pipe itself. In the case of water leakage phenomena, the water-leak wave is measured when it is transmitted in the pipe after being propagated through the water from the sound source. In a series of elastic wave propagation routes, the transmission coefficients of the pipe materials have the greatest effect on AE monitoring accuracy. From the perspective of elastic wave motion theory, the reflection and transmission of water-leak waves on the pipe surface can be treated as bilayer phenomena (water-material). In most cases where elastic waves are incident in the bilayer medium, the following relationship can be derived among the wave impedance ratio, the reflection coefficient, and the transmission coefficient:

$$\alpha = \frac{\rho_2 V_2}{\rho_1 V_1} \quad (2)$$

$$\beta = \frac{1-\alpha}{1+\alpha} \quad (3)$$

$$\gamma = \frac{2}{1+\alpha} \quad (4)$$

where ρ: density of medium, V: velocity of elastic wave.

Table 1. The characteristic of elastic wave in the bilayer medium
(Pipe materials - Water)

Pipe material	Sound impedance ratio(α)	Reflection ratio(β)	Transmission coefficient(γ)
PVC	1.53	-0.211	0.789
Concrete	5.33	-0.684	0.316
Steel	28.00	-0.931	0.069

Assuming that the sound impedance Z(=ρ·V) of materials (unit: $kgf/m^2 \cdot s$) is $Z_{water}=1.5\times10^6$ for (transported) water, $Z_{PVC}=2.3\times10^6$ for polyvinyl chloride (PVC) pipes, $Z_{con}=8.0\times10^6$ for concrete pipes, and $Z_{SP}=4.2\times10^7$ for steel pipes, the wave impedance ratio α, the reflection coefficient β, and the transmission coefficient γ will be as shown in Table 1**.**

The results of the investigation showed that the reflection coefficient of the incident wave depended on the quality of the material. For example, 93% of the incident wave was reflected in steel materials. In contrast, the reflection coefficient was only 21% in PVC. Similar trends were found for amplitude. In PVC, 79% of the wave amplitude was transmitted to the measuring point, as opposed to a mere 7% in steel materials. Elastic waves propagated in water showed significant decay at the stage of transmitting the pipe material and the decay properties depended on the pipe material. In AE monitoring, the material of the pipe to which the sensors were attached had an effect on the monitoring results; even phenomena at the same scale showed differences in AE parameters, due to differences in pipe materials. However, since only a few types of structural materials are used in pipelines, suitable AE monitoring can be taken by considering correcting measurement results beforehand based on the type of material.

Effect of pipeline structure on monitoring accuracy

In addition to pipe material, another factor affecting AE monitoring may be the pipeline structure. Either a branch-type pattern or a network pattern is used for pipeline systems. At the time the pattern is selected, the pipeline system can be quite varied. Previous studies have reported on attenuation (decrease in RMS voltage) in crooked or winding sections. Similar tendencies with AE monitoring have been mentioned by overseas researchers such as S. J. Vahaviolos(2001) and Amani Raad(2002). From the above information, auxiliary monitoring using wave guides, in addition to monitoring at concrete pit as proposed in this paper, make it possible to conduct measurements taking water pipeline structures into consideration. Given the above information, the AE measurement of water flow and leakage phenomena in pipeline facilities must consider structural characteristics in addition to material quality.

QUANTITATIVE EVALUATION OF WATER FLOW SIGNALS BY AE IN AN EXISTING PIPELINE REPARED

Investigating the effects of repairs on buried pipeline facilities

In this study, there are 3 types (cases) of measurement conditions:
--Case 1, the stage at which water leakage has been confirmed (before repairs are made)
--Case 2, the stage at which water is being drained from the pipe to prepare for the repair work (forced drainage).
--Case 3, the stage at which water is filled back into the pipe (after repairs have been completed).


Photograph 2. Defect in air valve

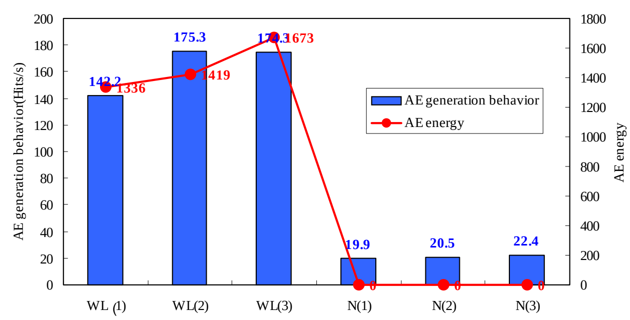


Figure 9. Relations between AE generation behavior and energy (water-leak and normal position)

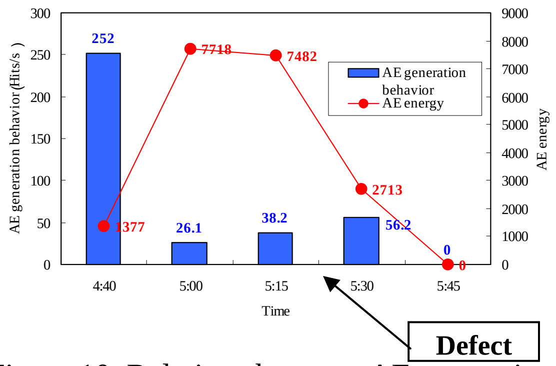


Figure 10. Relations between AE generation behavior and energy (forced drainage conditions)

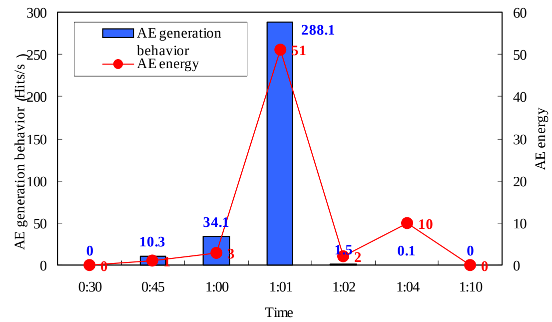


Figure 11. Relations between AE generation behavior and energy (add water conditions)

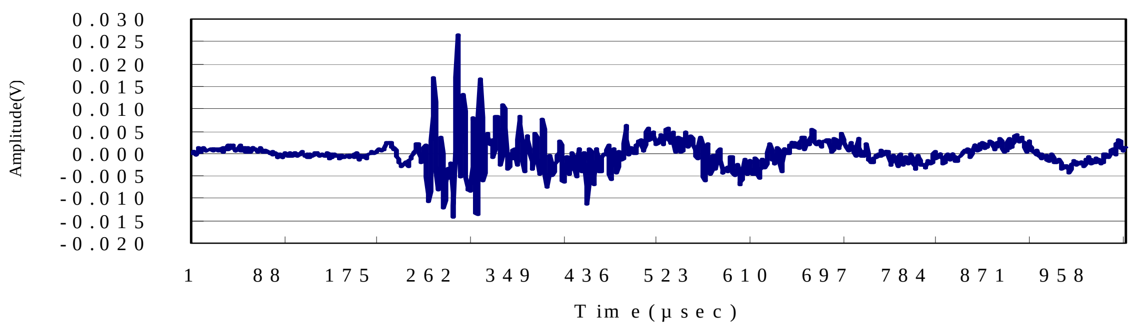


Figure 12. Elastic wave measured when float ball is completely fixed in air valve

For the AE measurements, a sensor was installed on the surface of the air valve where water leakage had been confirmed (leaking section), and measurements were taken for 30 seconds at 15-minute intervals. At the same time, measurements were taken under the same conditions in normal sections that had no leakage. The measurements were taken with resonance sensors under conditions of threshold value of 45dB and amplification of 60dB at the pre-amp and main amp.

Before repairs (Case1). The AE generation frequency at the leakage point (air valve) was 142.2 to 175.3(Hits/s), which was 7.8 times higher than in the normal section (Figure 9). This was a clear confirmation of the effect of the defect directly beneath the air valve shown in Photo. 2. Unlike generation behavior, the value for AE energy measured in the normal section was 0.0. In the water leakage section, a continuous wave was detected (Figure 3), but in the normal section, the only noise detected was from the traffic noise (Figure 6). AE energy was defined as a relative value having 1000-count energy when the 10V peak value continued for 1mmsec. At short bursts of AE (environmental noise), the measured value was 0.0. Given the above findings, the present measurements clearly showed that it was possible to use AE energy to distinguish between noise and water leakage.

During forced drainage (Case2). The case of drainage made in order to remove water using drain pump. At 4:40 a.m., when the measurements started, AE generation behavior showed a similar trend with Case 1 due to the effect of the leaking water (Figure 10). However, starting at 4:50 a.m., when forced drainage started, AE generation behavior decreased as the water level fell. AE energy of approximately 7,000 was recorded. This phenomenon apparently resulted from the propagation of water drainage sounds, and vibrations inside the pipe. At 5:45 a.m., the bobber inside the air valve dropped, signifying that the water have been completely drained at the air valve site. AE generation and energy were both 0.0.

Refilling water after repair work (Case3). AE measurements were taken when the repair work had been completed and water was being refilled. From 8:45 p.m. (immediately after starting to refill the water) until 12:30 a.m., AE was not detected. This was because the water level had not yet reached the air valve. From 12:30 a.m., when the water level inside the pipe reached the air valve, until 1:10 a.m., when the air valve have been completely filled with water, distinctive changes were detected. From 12:30 a.m. until 1:10 a.m., both the AE generation behavior and AE energy increased rapidly (see Figure 11). After that, the AE generation behavior decreased dramatically, but when the air valve bobber became completely fixed in place, elastic waves were found to be emanating from friction sounds of metals having high AE energy.

The above findings indicate that the results of pipeline facility repairs can be quantitatively investigated using AE monitoring.

CONCLUSION

In this study, the acoustic emission (AE) method is applied to the water flow signals (elastic wave) evaluation of the existing PC pipeline which is repaired with three experimental conditions after water-leak accidents. The first condition is a water leak phenomenon. The second condition is a water-drained condition in the pipeline before repairing. The third condition is being filled again in the pipeline after repairing the water-leak point. The analytical results show that water flow performance of the pipeline system could be quantitatively evaluated using AE parameters.

The monitoring accuracy is affected to distance decay and pipe material. Therefore, AE monitoring in pipeline system is necessary to make consideration of applied conditions in existing structures.

As for the relationship AE generation behavior and energy, hydraulic conditions in pipeline were evaluated. To conclude, water leak evaluation of the repaired pipeline system can be quantitatively evaluated through NDT monitoring using AE method.

REFERENCES

Amani Raad, Fan Zhang, Menad Sidahmed: Leak Detection by Acoustic Emission using Subspace Methods, J. Acoustic Emission, 20, pp.300-307, 2002.

JSCM-IIIB-5706: Monitoring method for active cracks in concrete by acoustic emission, 2003.

Kamiya, A., Morofuji, K., Enuma, K., Yamada, M. and Yuyama, S.: Quantitative Studies of Acoustic Emission due toLeaks from Water Tank, HPI Report, 40(4), pp.56-63,2002.

Nawa,N., Sonoda,K., Iwata,H. and Suzuki,T.: Survey and Evaluation Method for Deteriorated Agricultural Pipeline Function, JSIDRE, 70 (12) , pp.31-36, 2002.

Suzuki, T. Ikeda, Y. Tomoda, Y. Ohtsu, M.:Application of Acoustic Emission Method in Damaged Agricultural Pipeline for Functional Evaluation, JSIDRE, 72 (5) , pp.9-12, 2004.

Suzuki, T. Ikeda, Y. Tomoda, Y. Ohtsu, M.: Water-Leak Evaluation of Existing Pipeline by Acoustic Emission, J. Acoustic Emission, No.23, pp.272-276, 2005.

Vahaviolos, S.J., Miller, R.K., Watts, D.J., Shemyakin, V.V., Strizkov, S.A.: Detection and Location of Cracks and Leaks in Buried Pipelines using Acoustic Emission, J. Acoustic Emission, 19, pp.172-183, 2001.

REOPTIMIZING GLOBAL IRRIGATION SYSTEMS TO RESTORE FLOODPLAIN ECOSYSTEMS AND HUMAN LIVELIHOODS

Gregory A. Thomas[1]

ABSTRACT

The ultimate objective of the *Global Survey* project is to restore natural ecological functions, environmental services and the livelihoods they support to the downstream floodplains below the major dams of the world. There are today some 45,000 large dams operating in the world, the majority of which were built after World War II, and two-thirds of which are located in developing countries. Designed with a focus on economic and social benefits, these hydraulic projects have endangered the livelihoods of local communities who depend on rivers and their floodplains for their nutrition and livelihoods. In addition, they have caused pervasive damage to freshwater, riparian and estuarine ecosystems that support these human production systems.

Yet recent studies suggest that such damage to natural systems and riparian communities is often unnecessary and can be reversed by modifying the operations of these facilities in ways that do not significantly reduce—and can sometimes even enhance—their irrigation, power generation, and flood control benefits. Building on the potential of this recent work, NHI and its partners are undertaking a global inventory of the most promising opportunities and techniques to modify the operations of major water storage and diversion projects.

INTRODUCTION AND PROJECT OBJECTIVES

Background

The World Commission on Dams (WCD 2000) has chronicled both the economic benefits attributable to the 45,000 large dams built in 160 countries in the past half-century and the damage they have caused to water-dependent ecosystems and human production systems. Building on that work, the *Global Survey* will assess the feasibility of re-optimizing the major irrigation, power and flood management systems to restore a substantial measure of the lost ecosystem functions and human livelihoods in the downstream floodplains, without substantially diminishing the economic benefits for which the dams were constructed.

With few exceptions, the world's hydraulic infrastructure projects have been operated for a limited set of economic objectives and without consideration of the environmental consequences. Yet riverine ecosystems and the myriad species they support are shaped by, and dependent on, the timing, magnitude, duration, and frequency of flow patterns. Excessive changes in any one of these four variables can lead to the collapse of entire fisheries and ecosystems. The consequences for the downstream river basin can be

---

[1] President, Natural Heritage Institute; 100 Pine Street, Suite 1550, San Francisco, CA 94111; gat@n-h-i.org

profound. In most cases highly dynamic riverine systems are transformed by dams into static water delivery channels, reducing the diversity of habitat and species. Elimination of annual floods deprives riparian forest and wetlands of periodic inundation, effectively disconnecting the river from its productive floodplain habitats. Seasonal inflows of freshwater and nutrients into the ocean are diminished, disrupting the estuarine hydrodynamics that are the engine for the exceptional biological fertility at the freshwater/salt water interface: native fisheries suffer in the face of exotic invaders, seasonal natural and cultivated food sources are lost, pastoral use of the floodplain becomes impossible, game species are displaced, groundwater levels decline, and recreational and aesthetic values of a living river basin disappear.

Yet there are a number of water management techniques that can be employed to create substantial flexibility in how these dams and diversions are operated, opening up possibilities to restore lost ecological functions and processes. The *Global Survey* will pursue two converging lines of analysis:

(1) Identify the river reaches and floodplains downstream of major dams where restoration of periodic floodplain inundations in a managed fashion—emulating the natural hydrograph—would produce the greatest benefits in terms of restored aquatic ecosystems and human livelihoods and other land uses dependent upon natural groundwater recharge. To this end, the project is devising a rapid assessment tool to identify the best prospects for reoptimization. The objective of this reconnaissance level tool is to demonstrate that the number of dams that are good prospects for beneficial reoperation is far larger than has heretofore been realized and to thereby induce larger investments in the development of implementable reoptimization plans for the most promising facilities.

(2) Develop a “toolkit” of improved water management techniques that can provide the necessary flexibility in reservoir storage and release patterns to enable environmental flow regimes to be re-established. The types of water management techniques that can be applied to enable beneficial reoperation depend on the purpose served by the dam. We discuss this toolbox of techniques below.

Note that it is more accurate to describe the objective of the project as *reoptimization* of water management systems, rather than *reoperation*, because the techniques that we wish to explicate are those that can allow dams to improve their environmental performance while *continuing* to provide the water supply, power and flood control benefits for which they were initially constructed.

In recent years, increasing attention has been paid to the ecological benefits of reoperating dams to store and release water in a pattern that more closely resembles natural flow conditions with their seasonal variability (Acreman 2003). The aiming point is to operate the reservoir more as a run-of-the-river facility and less as a storage facility. This work defines the environmental water *demands* for the system. However, relatively little attention has been paid so far to techniques enabling these dams to make such environmental flow releases a permanent operational feature without reallocating water from economic to environmental uses. This may be regarded as the environmental water *supply* side of the system. This project is intended to fill that information gap.

The practicality of reoptimization ultimately reduces to the question of whether enough of the pre-development ecological and human production benefits can be restored to justify the costs of reoptimization, from the vantage point of full social accounting. Additional limiting factors – and hence cost-centers – include:

- i) the difficulties in re-establishing sediment processes downstream of dams (which serve as sediment traps) that may irreversibly transform the morphology of floodplains and deltas;
- ii) the intervening floodplain development that will constrain the magnitude of flood events that can be re-established; and
- iii) the physical limits of the dam and reservoir.

It is also significant that some reoperation techniques, particularly conjunctive water management, can increase the stored water yield and thus create new value in the system that can offset the costs of reoptimization.

The best prospects for reoperation will emerge where the floodplain benefits converge with the technical potential for dams to release environmental flows. Preliminary work suggests that we will find those circumstances in China, South Asia, Southeast Asia (the Mekong system), Brazil, West Africa and Southern Africa, among other regions. The number of dams that will be evaluated will be illustrative rather than exhaustive. The next section of this paper sets out the threshold considerations in selecting the dams that will be assessed for their reoperation potential.

Project Phases

The project envisions three phases. In the current and first phase, the project endeavors to identify 2-6 dams that are especially promising candidates for reoperation. The goal of the second phase is to develop concrete reoperation plans for these facilities. This will involve much more detailed and intensive analysis and modeling of operational alternatives. The third and final phase involves implementation of the reoperation plans by the dam operators and government departments.

DAM SELECTION CRITERIA

The database that we are constructing currently contains more than 500 dams. From this list, we intend to apply the consideration factors described herein to select ten to twenty dam systems for a reconnaissance level of assessment of reoptimization feasibility and benefit. As noted above, to make releases for environmental flow restoration possible, it is necessary to create flexibility in how these dams store and release water for irrigation, power generation and flood control. In this process, we will evaluate the technical, socio-economic, and legal/institutional feasibility of applying specific water management techniques to generate that operational flexibility. Several other pragmatic factors will

also bear on the selection of water management systems for reoptimization evaluation. The results of the analysis will be findings and recommendations on how reoperating plans might be developed for the most promising of these dams.
There are five interrelated factors to consider in selecting major water management systems for reoptimization evaluation. These are:

1) The hydrophysical, socio-economic, legal/institutional and political requisites for successful reoptimization;
2) The potential for rich restoration benefits in the downstream floodplain;
3) The availability and sufficiency of the requisite data;
4) Willing partners; and
5) Geographic considerations

The Hydrophysical, Socio-Economic, Legal/Institutional and Political Requisites for Successful Reoptimization

Large dams have been built for three main purposes in all regions of the world, although about 20% serve multiple functions (WCD, 2000). The purpose of the reservoir determines the operating characteristics and the extent to which the reservoir stores and releases water on a schedule that distorts natural flows. Since the objective of this project is to find reservoirs that can be reoperated without impairing their economic uses, the purposes of the reservoir will usually determine the types of techniques that can be applied to create the operational flexibility that can enable environmental flows to be maintained as a permanent operational feature.

- **Water supply reservoirs for irrigation** constitute half of the world's large dams, with the largest number in China, India, Pakistan, and the United States (WCD, 2000). These dams generally provide seasonal storage and in some cases inter-annual storage of water to buffer the variations in natural runoff. There are a variety of techniques for changing the management of irrigation water in ways that increase the storage and release flexibility. Irrigation projects that were built to counteract pre-existing groundwater depletion give rise to the possibility of conjunctive water management and the integration of surface and groundwater management. This type of storage flexibility may enable a considerable degree of environmental flow restoration (Purkey et al., 1998). Other options include reducing storage requirements through techniques to reduce physical losses to the system through better on-farm management and retiring waterlogged and salinized lands.

- **Hydropower reservoirs** store water to create hydrologic "head" for power production either at the dam or at some point downstream. Some of these facilities operate, more or less, on a run-of the-river mode where the reservoir is used simply to create the hydrologic head rather than to store water. Generally, these are facilities where the capacity of the reservoir is small relative to the annual flow of the river.

However, most hydropower reservoirs store and release water on a pattern to generate power during times of highest demand (peak power facilities). Large storage, relative to flow, is developed specifically to counteract seasonal variation in flows. Hydropower is particularly suited for meeting peaks because can be switched on very fast – unlike thermal power stations which need warm-up period) Electrical demands generally peak during particular times of day when, for instance, lights are turned on the evening or air conditioners are turned on in the later afternoon, and during particular seasons, such as summer for cooling or winter for heating. The inflow patterns are generally out of phase with these release patterns, creating unnatural flow patterns that can be highly disruptive to downstream ecosystems and floodplain livelihoods. If power reservoirs can be operated to release water at the same rate as the inflow into the reservoir, they can merely pass the natural hydrograph through the reservoir without disrupting stream flows. Thus, the goal is to convert storage reservoirs into run-of-the-river facilities to the extent feasible.

For facilities that follow the load curve, the major challenge is to investigate ways in which the role of the hydrodam in the mix of generators feeding the grid can be changed to allow the dam to operate as a base load rather than peak load facility so that daily and flow fluctuations can be avoided, and seasonal fluctuations can be synchronized with runoff. These "run of the river" facilities are not wholly, benign, however. They do intercept sediment flows, which are essential to the downstream eco-morphology, and they adversely affect temperatures and other water quality parameters.

- **Flood control reservoirs** capture the peak flow events and release this water more slowly after the storm passes. While disruptive of the natural hydrograph, flood control facilities can most easily be operated to permit seasonal inundation of floodplains for environmental and floodplain production benefits.

  The reoptimization goal with flood control facilities consists of creating conditions under which a larger fraction of the peak flow events can be allowed to pass through into the downstream floodplain. Thus, facilities designed to control a 20-year flood event might be reoperated to only control the 50-year flood events. Land uses in the floodplain will need to be modified to accommodate this periodic inundation. If the land use constraint is immutable, such as larger human settlements, high-value structures such as roads or bridges, or permanent crops such as orchards, it may be that increased inundation of the floodplain is simply not feasible. Facilities with such downstream characteristics may not be suitable for reoperation.

SUMMARY OF TECHNIQUES FOR REOPTIMIZATION

To summarize, the current list of techniques, organized according the main purpose of the dam, are these:

Irrigation dams

- Integrating groundwater and surface storage (conjunctive water management)
- Aquifer recharge and recovery (groundwater banking)
- Reductions in physical losses from irrigation systems (reducing evaporative losses in water conveyance and applications, reducing deep percolation to salty aquifers, etc.)
- Relocating points of diversion and return flow
- Water transfer arrangements
- Retiring waterlogged or salinized lands

Hydroelectric dams

- Changing the role and function of the hydrodam in the mix of generation facilities for the grid
- Substitution of daily peaking facilities
- Re-regulation reservoirs downstream of hydroelectric dams
- Pumped storage facilities to reduce the need to operate dams to follow electrical load curves
- Better coordination of cascades of dams to permit more flexible operation

Flood control

- Flood easements
- Flood routing and storage in retention basins
- Levee setbacks

All dams

- Building sluice gates that pass sediment downstream

The feasibility of each of these techniques will also depend upon whether certain physical, economic and legal/institutional conditions exist. For instance:

- For conjunctive management of surface and groundwater storage in the irrigation setting, the *physical requisites* may include the existence of dewatered aquifers with appropriate physical characteristics in the irrigation command area (due to pre-existing or current groundwater pumping), reservoirs that periodically spill water for flood control purposes, and the ability to connect the two. The Yellow River basin in China and the San Joaquin River basin in California are two settings in which these conditions are known to exist, but they are likely to be found in many places around the world. The *economic requisites* may consist of the ability of the farmers to afford conjunctively managed water. The *legal and institutional* requisites may revolve around who owns and can extract surface water stored in aquifers and whether water rights and entitlements are sufficiently well-defined and enforceable to enable water transfer arrangements to take place.

- To change the role that hydropower generators play in meeting the peak daily or seasonal demands of the grid to which it is attached, two strategies may be envisioned. Either those peak demands can be met by other hydropower dams, or by other types of generators, such as gas-fired turbines, which are generally quite suitable for peak power production. Both of these alternatives will have economic (and social and environmental) consequences , which may or may not make them feasible. Both may or may not be accomplishable by interconnecting existing electrical grids, and that in turn may or may not be legally or institutionally feasible. To take the first alternative as an example, a frequent occurrence around the world is that a cascade of hydropower dams is built on the same river and feeds into the same grid. Typically, one of those dams (not necessarily the terminal one, but likely one of the larger ones) effectively controls flows through the cascade and into the downstream floodplain. Modeling can reveal the extent to which it would be feasible to reoperate that dam to improve environmental flows (as a primary operational objective) and then reoperate some or all of the other dams in the cascade to make up for the peak power production lost in the targeted dam.

Moreover, the very goal of reoptimization will require analytical tools to weigh competing objectives and to design alternative operation protocols. For example, to balance the productive objectives of a multipurpose dam against the competing socio-economic and environmental objectives of uses in the downstream floodplain, it may be useful to develop a model that simulates the interactions between alternative operation scenarios and resulting biophysical and socio-economic processes, such as food production possibilities related to the extent of flood in an area of recession agriculture. This allows for a concrete analysis of the best overall scenario that can optimize outcomes with minimal trade-offs among competing uses. An optimization analysis and dam management protocol has been in place since 1997 at Manantali dam in the Senegal River Basin, and has allowed for the design of yearly artificial flood to protect recessional agriculture (IRD 2004). Such a tool could be enhanced to explicitly incorporate ecological objectives.

While the *Global Survey* will concern itself mostly with the physical factors that determine the feasibility of beneficial reoptimization, it will also consider the array of other factors that make reoptimization implementable. We have already alluded to some of the socio-economic, legal, institutional, and political requisites in the discussion above. Important such enabling factors include:

- The extent of economic subsidies to existing uses of large dams. Such subsidies affect the costs and benefits of displacing a portion of existing uses to accommodate environmental flow releases. Where irrigation or power generation subsidies are large and the benefits of environmental flows are appreciable, reoperation may be attractive from the standpoint of net social benefits.

- The affordability of the measures necessary to remove structures, resettle populations or obtain flood easements, and the willingness of public agencies to pay these costs.

- Laws and institutions at the national and local level, e.g., well-defined and enforceable water rights or entitlements.

- Additional legal/ institutional and political requisites may have to do with whether the codes authorize eminent domain in these circumstances and whether the authorized government agencies are willing to exercise that power.

There are also a number of political factors that cannot be ignored. Dams in countries where the planning process is impervious and impermeable, where official corruption is too substantial, where proposals from NGOs have little traction, or where civil conflict is rampant are probably not good candidates for this work.

By distilling the requisites for successful application of reoperation techniques that can be applied to these types of water management systems, we can construct a rapid assessment tool for selecting those that warrant the investment of larger resources to evaluate their potential. We have constructed such a tool in the form of a decision tree. It is attached to this paper in Appendix.

THE POTENTIAL FOR RICH RESTORATION BENEFITS IN THE DOWNSTREAM FLOODPLAIN

The project will concentrate on those downstream river reaches where flow restoration will produce the largest ecological and human livelihood benefits. River reaches that supported the richest array of native species before development, and suffered the greatest loses as a result of development, are presumptively the ones that would provide the richest benefits if flows could be restored.

Unfortunately, however, there is a paucity of data on baseline conditions before dam construction that would permit comparisons with conditions after construction. Some analytical surrogate for biodiversity losses, such as the depletion of fish species and abundance, will need to be developed. Similarly, the analyses of hydrologic and biologic alteration of rivers are reported at the basin scale, not at the scale of the river segments immediately downstream of particular dam sites. This scale limitation will permit us to draw conclusions regarding generalized impacts only. Cumulative effects of cascades of dams are another complication.

In these circumstances, the benefits of reoperating a single facility are less clear. Moreover, as noted again below, displaced human livelihoods may not be recoverable and some physical effects of dams are irreversible, such as morphological changes in stream channels and deltas.

In general, we will assume that the reaches of rivers that nourish (or could nourish) broad alluvial floodplains, broad alluvial valleys (such as those associated with savannas in Africa and flood prone semi-tropic basins in Asia), wetlands systems, deltas and estuaries are the most important from a biodiversity and human production system standpoint. These tend to be found in the lower reaches of the rivers which are affected by the large storage dams that control freshwater flows in to estuaries and/or block migration of anadromous species. Floodplains are areas of high biodiversity and provide important habitat for riverine fish (Ward 1998; Welcomme 1979). Based on research conducted mainly in the tropics, scientists have described a 'flood pulse advantage' in which rivers that are connected to functioning floodplains produce a significantly greater biomass of fish per unit area than do rivers disconnected from floodplains or lentic water bodies, such as reservoirs (Bayley 1991).

THE AVAILABLITY AND SUFFICIENCY OF REQUISITE DATA

The data requirements for this project are driven by the selection criteria that are chosen, and the availability of the necessary data itself becomes a criterion for screening projects for more detailed examination. Under the time and resource constraints of this project, we will necessarily rely on information that has already been developed and expert opinion, with additional limited fieldwork.

WILLING PARTNERS

The active participation of the national agencies that plan, regulate, manage and operate the dams and their water management systems is indispensable. That is because these are the repositories of the data and technical expertise necessary to evaluate reoptimization potential, and because the results are much more likely to be implemented if these national agencies take early ownership in the program. The willingness of the key government officials to cooperate in the reoptimization evaluation is therefore a threshold selection criteria.

The practical necessity of working with government agencies in the affected countries also suggests that we work in countries that have already displayed some predisposition or inclination to consider environmental flows in the operation of dams. To date environmental flow methodologies have been applied in 52 countries, albeit often on a very limited basis (Tharme, 2003). The developing countries noted are:

- Brazil
- Cambodia
- Cameroon
- Chile

- India
- Indonesia
- Kenya
- Lesotho
- Mali
- Mauritania
- Mexico
- Mozambique
- Namibia
- Nigeria
- Pakistan
- Senegal
- South Africa
- Tanzania
- Turkey
- Zambia
- Zimbabwe

In addition, China has indicated a strong interest in dam reoptimization to improve environmental flows.

There is also an important role for in-country NGOs in suggesting reoperation strategies, providing information, opening doors with government collaborators, and creating a favorable climate of public opinion for the consideration of dam reoptimization. NGOs may also play a key role, due to their extensive local knowledge, in assessing the potential for natural resource and human livelihood benefits from re-establishing more natural flow regimes in the floodplains downstream of the major dams.

Incidentally, there is also an important role to be played by the intergovernmental agencies in this project. The World Bank has become keenly interested in this project. The Global Environmental Facility has also indicated an interest.

GEOGRAPHIC CONSIDERATIONS

We will emphasize countries where development assistance is most likely to be available for dam reoptimization projects: dam reoptimization, even when substantially maintaining the current economic uses, will usually not be free of cost. While reoperation strategies that also augment water supplies such as can be accomplished with conjunctive water management may pay for themselves, in many cases the environmental restoration and human livelihood benefits will not generate a revenue stream that can compensate the costs of dam reoperation. Thus, while on the full social accounting ledger, dam reoperation may often be “cost-effective”, some external source of funding will usually be necessary to implement reoperation plans. Also, we wish to identify lost ecological processes that affect human livelihoods. These losses disproportionately affect subsistence users of the watershed. For both of these reasons, the project is inclined to emphasize dams in the developing world.

Moreover, the potential that successful reoperation experiments will be widely replicated may also be advanced by emphasizing the countries with the largest number of dams, on the assumption that successful experiments are most likely to be replicated in those same countries. Rebecca Tharme and the World Commission on Dams have published useful information on the numbers of major dams in various countries of the world, as illustrated in Table 1 (reprinted from Tharme 2003):

Table I. The top 20 countries worldwide by number of large dams (adapted from WCD, 2000)

	Country	ICOLD World Register of Dams 1998	Other sources	Percent of total dams
1	*China	1855	22 000	46.2
2	*United States	6375	6575	13.8
3	*India	4011	4291	9.0
4	*Japan	1077	2675	5.6
5	*Spain	1187	1196	2.5
6	Canada	793	793	1.7
7	South Korea	765	765	1.6
8	Turkey	625	625	1.3
9	Brazil	594	594	1.2
10	France	569	569	1.2
11	South Africa	539	539	1.1
12	Mexico	537	537	1.1
13	Italy	524	524	1.1
14	United Kingdom	517	517	1.1
15	Australia	486	486	1.0
16	Norway	335	335	0.7
17	Germany	311	311	0.7
18	Albania	306	306	0.6
19	Romania	246	246	0.5
20	Zimbabwe	213	213	0.4
	Others	3558	3558	7.0
	Total	**25 423**	**47 655**	**100.0**

*Estimates for the numbers of dams in these countries (particularly China) as well as for the Russian Federation, differ according to available data sources.
ICOLD, International Commission on Large Dams.

Combining this information with the bias toward developing countries, the preference for countries that have exhibited an interest in environmental flow restoration, and the political realities noted above, the following countries appear to warrant priority consideration:

Asia
China
India
Pakistan
Cambodia
Indonesia

Western Africa
Senegal

Mali
Mauritania
Cameroon
Nigeria

Eastern and Southern Africa
South Africa
Tanzania
Zambia
Kenya
Lesotho
Mozambique

Latin America
Brazil
Mexico

Eastern Europe and the Middle East
Turkey (and its downstream riparian Iraq?)
Albania
Romania

With all of these considerations in mind, we are defining country-specific or region-specific components of the project where we expect to be able to make the most headway. China promises to be fertile ground for this project, as the Minister of Water Resources himself will be leading the consortium of Chinese partner institutions, including the Institute for Water Resources and Hydropower Research, the Chinese Academy of Sciences, Tsinghua University (the leading technical university in the country), and others to investigate the prospects for reoptimization among major Chinese dams. The second promising area for intensive work is Western Africa, specifically, the Senegal, Niger and Volta River systems. The other areas targeted for special attention include Brazil and Southern Africa.

LIMITING FACTORS

Before concluding, it is important to acknowledge certain inherent limitations in what we can hope to achieve in this project, given certain physical constraints and limitations:

- The project cannot hope to restore the natural hydrograph in its entirety in developed rivers while substantially maintaining the current economic uses of these dams. At most, we can hope to restore the flood plain inundations that naturally occur every 2 or 5 or perhaps10 or even 25 years. But we generally cannot hope to restore the 50 year or 100 year events. That means that the ecological benefits associated with large flood events cannot be recaptured through dam reoperation.

- Even beneficial flow alternation will not restore the sediment transport and deposition processes necessary to restore downstream ecological conditions and floodplain productivity.

.

- Floodplain encroachment by structures and land uses may limit the feasibility of controlled reintroduction of floodplain dynamics.

- The capacity of the release works to permit variability in streamflows may also constitute a physical constraint on reoperation.

OUTCOMES AND POLICY IMPLICATIONS

In a field dominated by conflict, stalemate and zero-sum thinking, the project offers a creative solution and a way to bridge the professional gulf between engineers and ecologists. Specifically, this work will lead to the pursuit of feasible restoration projects by the national governments and international assistance agencies. The results of NHI's *Global Survey* project will feed directly into the World Bank's Water Program and its stated preference for projects that improve the performance and use of existing dams (World Bank 2003). The project will also advance the Bank's environmental directive to integrate biodiversity concerns into large hydraulic infrastructure projects.

The project will also demonstrate and transfer a toolkit of techniques that can we used more widely by local conservation interests to effectively advocate for restoration initiatives far beyond the initial opportunities list that will emerge from this project. This will help implement two of the strategic priorities of the World Commission on Dams; first, the objective of restoring, improving, and optimizing the benefits from existing large dams and identifying opportunities for mitigation, restoration and enhancement; and secondly, the objective of sustaining the livelihoods of river-dependent communities by "releasing environmental flows to help maintain downstream ecosystem integrity and community livelihoods" (WCD, 2000). In addition, the NHI project will fill critical data gaps identified by the WCD as essential for strategic planning, namely improved understanding of the extent to which managed floods can offset the impacts of dams on downstream ecosystems and livelihoods, the effects of dams on downstream ecosystems, and techniques for improving the conjunctive management of surface and ground water.

Finally, this work will provide a concrete step forward in the implementation of measures to enhance the sustainability of major water management systems, such as those set forth in the International Hydropower Association's Sustainability Guidelines (2004). Indeed, the reoptimization toolkit and the set of demonstration cases developed under this project will open a path to many more opportunities in which the detrimental social and environmental impacts of major hydraulic infrastructure, including hydropower dams, are avoided or substantially mitigated.

REFERENCES

Acreman, A.C. 2003. Water Resources and Environment: Technical Note C.3. *Environmental Flows: Flood Flows.* The International Bank for Reconstruction and Development/The World Bank. Washington, D.C., U.S.A.

Bayley, P. B. 1991. The flood pulse advantage and the restoration of river-floodplain systems. Regulated Rivers: Research and Management 6:75-86.

International Hydropower Association. 2004. Sustainability Guidelines.

IRD. "Optimisation de gestion de barrage: le barrage de Manantali sur le fleuve Sénégal" by Jean-Claude Bader and Jean-Pierre Lamagat in Lettre No. 17 Programme International Géosphère-Biosphère – Programme Mondial de Recherches sur le Climat (PIGB-PMRC), 2004.

Purkey, T., Thomas, G. et al (provide full author list). 1998. Feasibility Study of a Maximal Program of Groundwater Banking. Natural Heritage Institute, San Francisco, California, U.S.A.

Tharme, R. E. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19: 397-441.

Ward, J. V. 1998. Riverine landscapes: biodiversity patterns, disturbance regimes, and aquatic conservation. Biological Conservation 83(3):269-278.

Welcomme, R. L. 1979. Fisheries ecology of floodplain rivers. Longman Group LTD, London, United Kingdom.

World Bank. 2003. Water – A Priority for Responsible Growth and Poverty Reduction: An Agenda for Investment and Policy Change. Water Resources Management working paper available at www.worldbank.org/water.

World Commission on Dams. 2000. Dams and Development: A New Framework for Decision-Making. Earthscan Publications Ltd, London, United Kingdom.

APPENDIX

Coarse Screening Tool to Identify Major Dams that Are Promising Candidates for Beneficial Reoperation

The technical considerations reflected in the template are of two types: (1) the physical attributes of the reservoir and the downstream channel/floodplain that make them good prospects for restoration of ecosystems and floodplain livelihoods, and (2) the physical attributes in the irrigation, electrical distribution or flood management system that are needed to apply the various improved management techniques. The simplified data requirements for performing this initial level of screening are summarized in Box 1. Boxes 2-3 present a routine for performing this type of screening.

Box 1: Data requirements for assessment of reoperation potential

The ability to assess a water management system for reoperation opportunities depends upon access to a wide variety information. Some of this data is easily obtainable in the form of the engineering specifications of system facilities (i.e. structures operated for water storage, conveyance, power generation, etc.) and hydrologic measurements (i.e. gauged discharge). However, other factors that are important in the assessment of reoperation strategies may be known only in a very general sense (e.g. existence of a dewatered aquifer) or may elude quantification altogether (e.g. degree of encroachment on the floodplain). Data requirements can be grouped into six main categories. In order of increasing difficulty to obtain, these are:

1) *Engineering specifications of the dam and reservoir*
- Purpose of dam/reservoir
- Volume/Surface Area/Elevation Relationships
- Height of dam
- Storage capacity
- Generating capacity
- Release works
- Operating authority

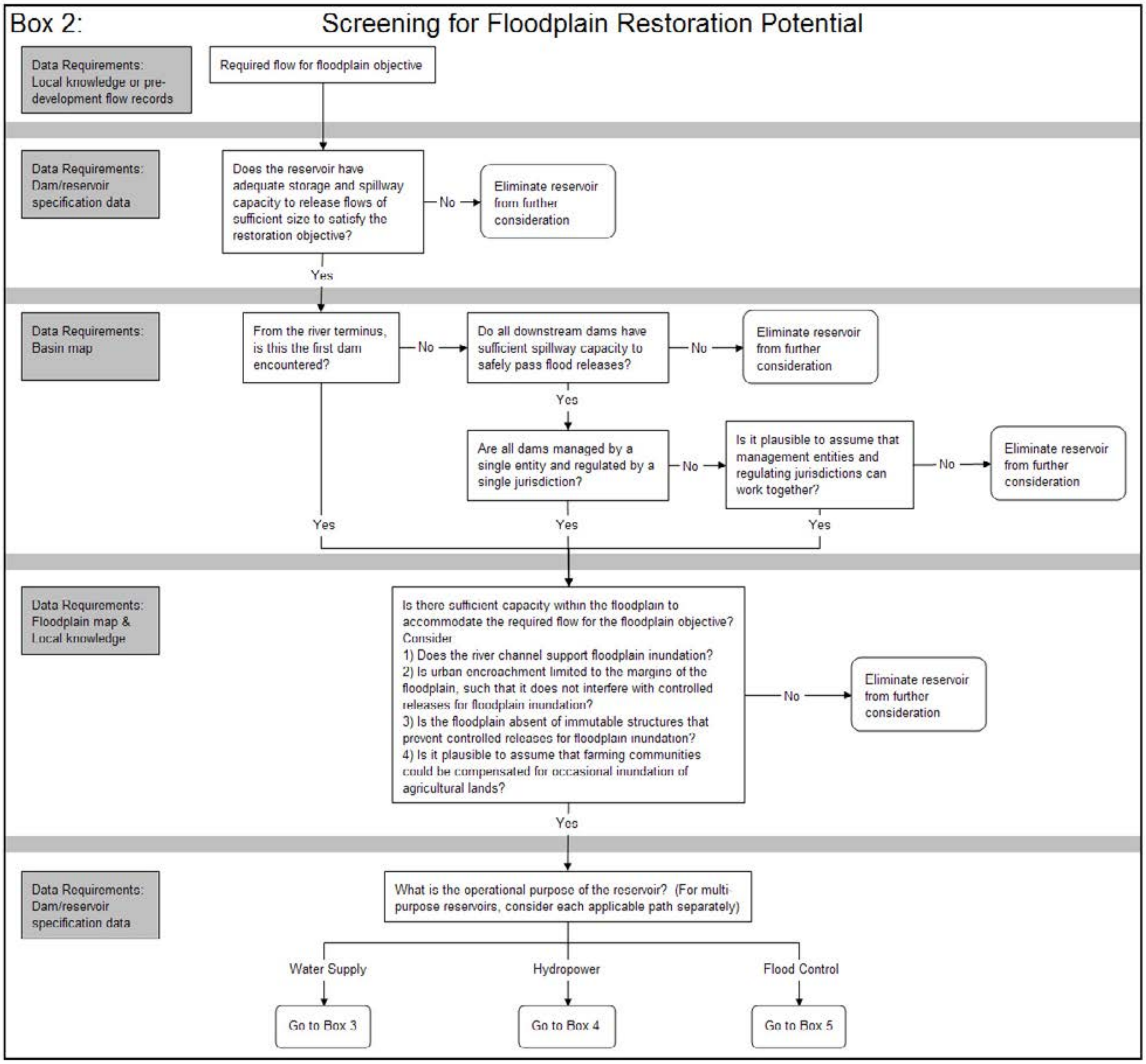
2) *Spatial relations of the floodplain and water service facilities within the watershed*
- Map of watershed indicating position of
  - i. Reservoir(s)
  - ii. Service area (i.e. cities, irrigated agriculture, etc)
  - iii. Restoration target
- Map of floodplain indicating
  - i. Position of immutable structures (e.g. roads, bridges, factories, hospitals, etc.)
  - ii. Land use

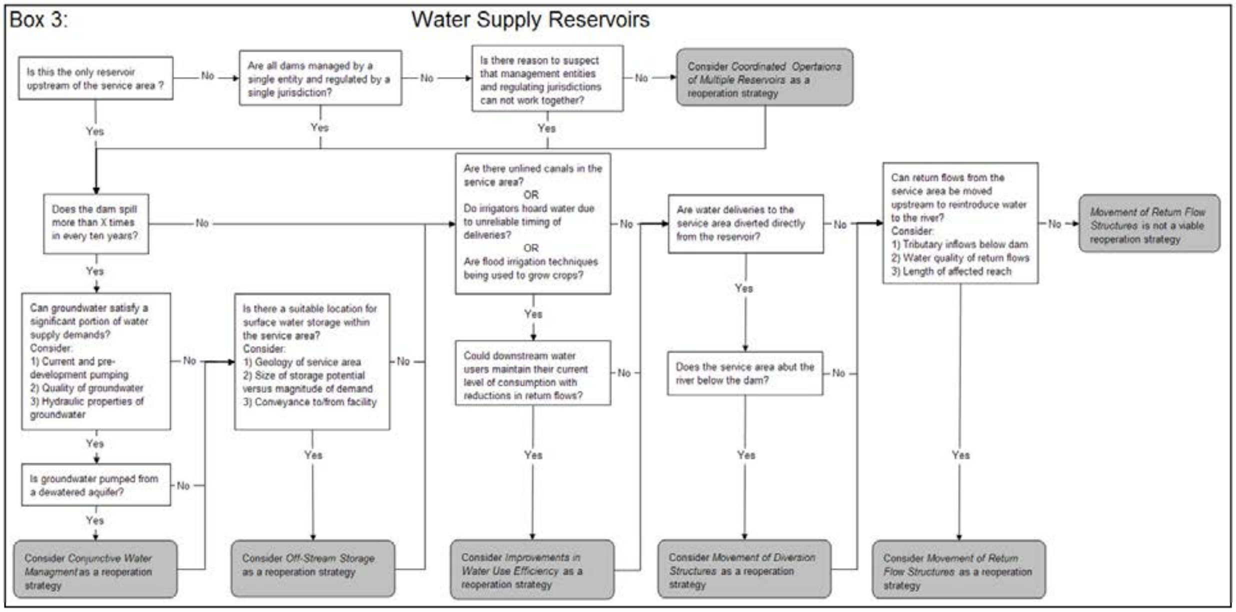
3) *Historical timeseries data of operations*
- Reservoir inflows
- Reservoir releases
- Actual hydropower generation
- Spills
- Changes in storage
- Evaporative losses

4) *Characterization of the service area demands and infrastructure*
- Connectedness of energy grid
- Timing and magnitude of demands (consumptive and power usage)
- Conveyance to/from service areas
- Spatial distribution of demands
- Cropping patterns
- Groundwater pumping
- Flood risk tolerance/exposure

5) *Institutional arrangements*
- System of water rights
- Legal mandates
- Trans-boundary treaties

6) *Economic considerations*
- Pumping costs
  - i. Groundwater pumping
  - ii. Lifting water to/from river
- Construction costs
  - i. Conveyance/return flow structures
  - ii. Storage facilities
  - iii. Interconnecting energy grids
- Revenue losses due to
  - i. Reduced hydropower generation
  - ii. Increased groundwater pumping
- Technology investments
  - i. Canal lining
  - ii. Irrigation equipment
- Purchases
  - i. Conservation easements
  - ii. Water rights


Box 2:
Screening for Floodplain Restoration Potential
Data Requirements: Local knowledge or pre-development flow records
Required flow for floodplain objective
Data Requirements: Dam/reservoir specification data
Does the reservoir have adequate storage and spillway capacity to release flows of sufficient size to satisfy the restoration objective?
No
Eliminate reservoir from further consideration
Yes
Data Requirements: Basin map
From the river terminus, is this the first dam encountered?
No
Do all downstream dams have sufficient spillway capacity to safely pass flood releases?
No
Eliminate reservoir from further consideration
Yes
Are all dams managed by a single entity and regulated by a single jurisdiction?
No
Is it plausible to assume that management entities and regulating jurisdictions can work together?
No
Eliminate reservoir from further consideration
Yes
Yes
Yes
Data Requirements: Floodplain map & Local knowledge
Is there sufficient capacity within the floodplain to accommodate the required flow for the floodplain objective? Consider
1) Does the river channel support floodplain inundation?
2) Is urban encroachment limited to the margins of the floodplain, such that it does not interfere with controlled releases for floodplain inundation?
3) Is the floodplain absent of immutable structures that prevent controlled releases for floodplain inundation?
4) Is it plausible to assume that farming communities could be compensated for occasional inundation of agricultural lands?
No
Eliminate reservoir from further consideration
Yes
Data Requirements: Dam/reservoir specification data
What is the operational purpose of the reservoir? (For multi-purpose reservoirs, consider each applicable path separately)
Water Supply
Hydropower
Flood Control
Go to Box 3
Go to Box 4
Go to Box 5


Box 3:
Water Supply Reservoirs
Is this the only reservoir upstream of the service area ?
Are all dams managed by a single entity and regulated by a single jurisdiction?
Is there reason to suspect that management entities and regulating jurisdictions can not work together?
Consider Coordinated Opertaions of Multiple Reservoirs as a reoperation strategy
Does the dam spill more than X times in every ten years?
Are there unlined canals in the service area?
OR
Do irrigators hoard water due to unreliable timing of deliveries?
OR
Are flood irrigation techniques being used to grow crops?
Are water deliveries to the service area diverted directly from the reservoir?
Can return flows from the service area be moved upstream to reintroduce water to the river?
Consider:
1) Tributary inflows below dam
2) Water quality of return flows
3) Length of affected reach
Movement of Return Flow Structures is not a viable reoperation strategy
Can groundwater satisfy a significant portion of water supply demands?
Consider:
1) Current and pre-development pumping
2) Quality of groundwater
3) Hydraulic properties of groundwater
Is there a suitable location for surface water storage within the service area?
Consider:
1) Geology of service area
2) Size of storage potential versus magnitude of demand
3) Conveyance to/from facility
Could downstream water users maintain their current level of consumption with reductions in return flows?
Does the service area abut the river below the dam?
Is groundwater pumped from a dewatered aquifer?
Consider Conjunctive Water Managment as a reoperation strategy
Consider Off-Stream Storage as a reoperation strategy
Consider Improvements in Water Use Efficiency as a reoperation strategy
Consider Movement of Diversion Structures as a reoperation strategy
Consider Movement of Return Flow Structures as a reoperation strategy
Yes
No

WATER MANAGEMENT TECHNOLOGIES FOR SUSTAINABLE AGRICULTURE IN KENYA

Herbert G. Blank[1]
Stephen N. Ngigi[2]
I.V. Sijali[3]

ABSTRACT

Improving food production in Kenya, as well as elsewhere in sub-Saharan Africa (SSA), is a daunting problem. Agricultural production is generally low, averaging less than one ton per hectare, which translates to a continuing cycle of poverty for millions of smallholder farmers. Improved utilization of water resources for agricultural production is an important prerequisite for increasing food production and incomes. This paper reports on experiences with a number of water management technologies and approaches in Kenya that are leading to sustainable increases in agricultural production and increased employment and incomes for smallholder farmers. Among these improvements are rainwater harvesting, improved performance of smallholder irrigation schemes, micro-irrigation technologies, and the participation of smallholders in export-oriented vegetable and other high-value crops production. Farmers who have access to seasonal water runoff can improve production with rainwater harvesting technologies. Modest investments and technical support have measurably improved the performance of existing smallholder schemes in Kenya. Micro-irrigation technologies, such as treadle pumps and low head drip kits, have provided farmers with low-cost methods of improving water management and agricultural production. Smallholder farmers throughout Kenya are participating as outgrowers in the production of export-oriented crops, meeting international quality and safety standards and substantially increasing incomes. The paper discusses these promising technologies and highlights recent research and interventions.

INTRODUCTION

Agricultural production in Kenya, as in most of sub-Saharan Africa (SSA), has long been stagnant with per capita production decreasing 33% between 1980 and 2000 (Earthtrends, 2006). The generally accepted wisdom is that the green revolution, which boosted Asian countries' production, bypassed African countries. A number of reasons are given for this missed opportunity: lack of transportation and marketing infrastructure, poor adoption rates of new varieties, lack of reasonably priced fertilizer, poor governance in the countries involved, poor water resource availability, and lack of investment in irrigation. Kenya's agriculture, like many other countries in the region, is highly susceptible to drought. Despite this grim picture, Kenya's economy (GDP) grew at the rate of 5.5% in 2005 (CIA, 2007). While irrigated agriculture comprises only 1.5% of total land under agricultural production, it contributes 18% of the value of all agricultural produce (Mwarasomba, 2006). This paper updates some of the technologies and approaches described in a more detailed earlier publication (Blank et al. 2002). One of the

[1] Consultant, Bend, Oregon, hblank@yahoo.com
[2] Food and Agriculture Organization of the United Nations, Entebbe, Uganda, s.ngigi@faonile.org
[3] Head Irrigation and Drainage, Kenya Agricultural Research Institute, irrigation@iconnect.co.ke

greatest niche opportunities is to supply fresh horticulture and floriculture crops to the European market during the winter months. Private investors in a number of SSA countries have seized on this opportunity. For example in Kenya, one company weekly exports 500 tons of cut flowers and vegetables to Great Britain via a dedicated fleet of large jet aircraft (Flamingo Holdings, 2007).

Agriculture is the major economic activity for 75 to 85% of the populations of the SSA countries (Ngigi, 2003). The vast majority of this activity is subsistence farms, reliant on rainfall and subject to drought. A major assistance to these subsistence farmers would be affordable rainwater storage for supplemental irrigation and adoption of drought resistant crops—the first of the approaches discussed in this paper.

RAINWATER HARVESTING

One of the promising solutions to increase agricultural productivity in SSA is upgrading rainfed agriculture through rainwater harvesting and management (RHM) systems. RHM systems are diverse and range from in-situ moisture conservation to large runoff storage systems and flood diversion and spreading (spate irrigation).

Rainwater Harvesting Research

Ngigi (2006a) conducted research on rainwater harvesting in Kenya and other countries in SSA as part of his PhD dissertation. The results of his study revealed that there a number of viable RHM systems that can improve agricultural production in semi-arid environments, although their effectiveness is limited by high water losses, inadequate storage capacity, poor water management, high occurrence of dry spells and drought, farmers' risk aversion, and financial constraints to invest in new farming systems.

On-farm storage systems for supplemental irrigation were found to be an economically viable alternative for smallholder farmers. A simulation of seasonal runoff using 16 years of rainfall records was carried out for a typical semi-arid environment in Matanya, Kenya (Figure 1 locates geographic placenames discussed in this paper) with average rainfall of 787 mm yr^{-1}. Rainfall was concentrated in two seasons per year, with average rainfall of 209 mm and 295 mm respectively. The simulation determined the reliability of a RHM system with a catchment size of 0.5 ha and a cropped area of 0.2 ha in meeting supplemental irrigation requirements. Despite relatively small landholdings, the availability of catchments to generate adequate runoff was not a limiting factor. The study found that grazing land generated adequate runoff for filling 50 m^3 farm ponds. Other opportunities include diversion of runoff concentrated by roads, footpaths and cattle tracks.

Optimal design parameters for sizing storage ponds were developed at the 80% reliability level. Optimal designs would improve overall system reliability, and reduce hydrological risks and crop failures. A benefit-cost analysis of a 50 m^3 pond and low-head drip irrigation system with total investment cost of $650 showed a net increase in income of $150 per season for an improved RHM system versus the conventional dryland system, with a payback period of about four seasons, or two years.

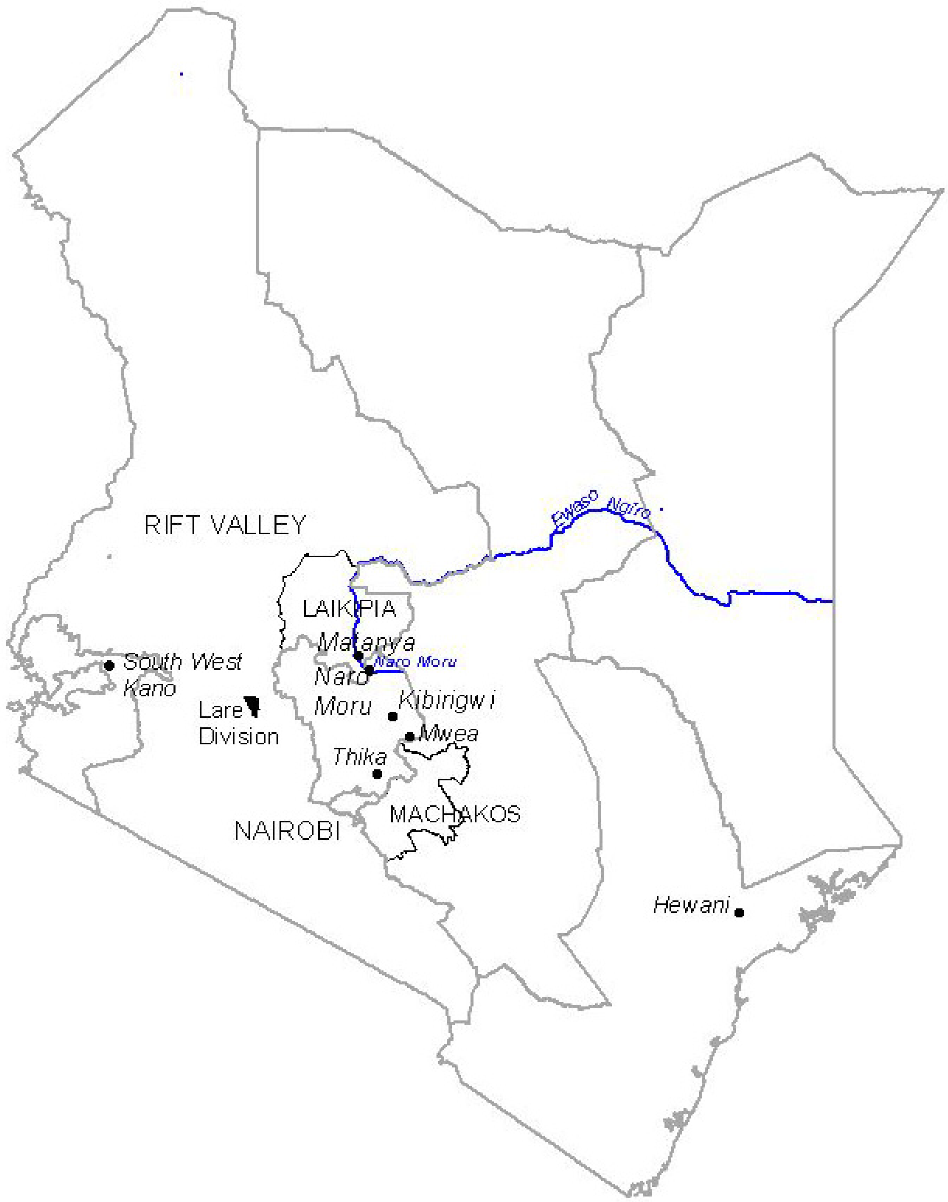


Figure 1. Location map of irrigation sites in Kenya

A study of on-farm ponds was carried out in the semiarid Laikipia area of Kenya with average rainfall ranging from 500 to 900 mm yr^{-1} (Ngigi, 2003). One of the survival strategies adopted by recently settled farmers was to construct on-farm ponds. The pond sizes ranged from 50 to 1500 m^3, with the storage potential varying by pond size and water losses due to seepage and evaporation. Most ponds were able to store water for 4 to 16 weeks after the cessation of rain, thus allowing for production using the stored water as supplemental irrigation. This technology is adaptable to a large part of the district.

Although RHM systems reduce the impacts of drought, their adoption is affected by high investment costs, the relatively low economic status of farmers, farmers' risk aversion, inadequate design, and poor water management. Although promising, RHMs alone cannot assure sustainable production. The need for improved agronomic practices, such as timely planting to take advantage of expected rainfall, cannot be over-emphasized. The challenge is to convince poor and risk-averse smallholder farmers that they can benefit by improving their agricultural production systems. An integrated approach is a prerequisite for achieving sustainable solutions.

The Lare Experience

While in general Kenyan farmers have not adopted rainwater harvesting, farmers in certain areas have adopted these techniques to an impressive degree. One such area is the Lare Division of Nakuru District. This agricultural area has a bi-modal precipitation pattern ranging from 600 to 1000 mm yr^{-1} with little access to ground water or perennial streams (Mati and de Vries, 2005). In a project conducted between 1998 and 1999, farmers were trained in various rainwater harvesting technologies. This project was a collaboration between Kenya Agricultural Research Institute (KARI), Egerton University, local NGOs, Ministry of Agriculture (MoA) and the United Nations Development Program. Training modules were developed to empower farmers to be able to do their own site selection, calculate water-storage capacity, construct and maintain water pans, and use the water for irrigation of crops suitable to local conditions. Treadle pumps were introduced to draw water from the pans to the cultivated fields. Since the project ended, the adoption rate for rainwater harvesting has continued to grow. In 1998, about 409 households had runoff harvesting systems, these increased to about 1,030 households by the end of 1999, and to 2,000 by August, 2004. Recently, using satellite imagery, Malesu and others (2006) found nine farm ponds per square kilometer in the Lare area, with most households possessing ponds. In addition to farm ponds, researchers found that farmers use other rainwater harvesting techniques as well, including roof catchments and in-situ soil moisture conservation such as pits and runoff farming.

Farmers have identified several problems which affect adoption: lack of information on proper sizing and other design information, and high infiltration rates experienced with some types of soils. These factors limit adoption to a wider group of farmers. Economically, farm ponds appear to make good economic sense. In Lare, farmers are less prone to drought and report increased production throughout the year. Milk production has increased through increased fodder production and better livestock water availability, and farmers report savings in labor costs that were previously expended to obtain water from distant sources.

Environmental Effects

In general, the negative environmental impacts of RHM systems are minimal. Ground catchment systems for community use and individual farm pond systems in Lare had positive environmental impacts by reducing storm runoff and erosion, and stimulating tree planting. Questions about ground water recharge remain, although it is clear that seepage and deep percolation from ponds contributes to ground water recharge. Ngigi (2003) found that adoption of RHM systems in Machakos District led to rejuvenation of springs downstream that had ceased to flow. There is concern that RHM systems may intercept runoff in the upstream part of the catchment, thus depriving potential downstream users of their share of the resource.

The Ewaso Ng'iro River basin has been studied by numerous researchers (Gichuki, 2003). Excessive water extraction by upstream irrigators has resulted in diminished river flows. Irrigators compete with downstream pastoralists who need water for livestock and with the needs of wildlife and the tourism industry. For example, in the Naro Moru sub-basin, only 25 of 100 irrigators have permits, and only half of the permits have been authenticated by the Ministry of Water and Irrigation. While it has been proposed that water users associations would improve water resources management in the Ewaso Ng'iro basin, reality dictates that a suitable solution would be to develop more upstream storage.

RHM systems in the Ewaso Ng'iro basin can provide an alternative water source that could reduce the demand on river flows and over-extraction during dry seasons (Ngigi, 2006a). RHM systems can be small to medium on-farm storage structures, such as are common in Lare, or can be off-stream storage reservoirs for larger communities. These structures would provide storage for excess runoff and flood flows that would be stored for use during low flow periods. By storing excess rainy season runoff and reducing dry season abstractions, flows would be more evenly distributed and available to downstream users throughout the year. The Government of Kenya (GOK) Water Act requires applicants for water permits to have facilities for 90-day storage. Unfortunately, stricter compliance of this condition is needed.

An evaluation of RHM systems in Ethiopia, Uganda, Kenya, and Tanzania identified some environmental issues that need to be addressed (Ngigi, 2003). These issues include increased mosquito and snail populations in open ponds, soil erosion along inlet channels, poor water quality, and risk of drowning in deep ponds. On the other hand, RHM technologies such as terracing generally reduce soil erosion by capturing sediment. Rainwater harvesting from rooftops for domestic use generally provides good quality water if minimal precautions are taken. Inadequately designed or constructed dams, spillways and canals also are environmental hazards. The study noted that expansion of RHM systems in upstream areas would not significantly deprive downstream water users of the resource.

A study of rainwater harvesting in Syria, Pakistan and Egypt looked at the impacts of the technologies at different spatial scales (Ali et al., 2007). At the micro-catchment scale (25-50m^2) in Syria, the researchers found insignificant localized effects downstream. At larger spatial scales, the study found greater effects. At the farm-scale in Pakistan under low rainfall conditions, the study found conflict among farmers who were competing for the limited water resource. At the larger watershed scale (i.e. between villages) in Egypt, the study found the potential for larger upstream-downstream impacts. For example, farmers often construct bunds across dry wadi beds to capture runoff. During high rainfall events, these bunds may break and can cause chain breaching and heavy soil erosion, destruction of property, and even loss of human life downstream. Nevertheless, despite some of the identified issues, the positive socio-economic and environmental impacts of RHM systems outweigh the negative impacts in the Kenya cases.

IMPROVING SMALLHOLDER IRRIGATION SCHEMES

The Improving the Performance of Irrigation in Africa (IPIA) project in Kenya, funded by the French government, attempted to increase performance of irrigation schemes through relatively low cost interventions. The aim was to develop irrigation as a profitable enterprise through development and dissemination of appropriate technologies, irrigation capacity building for farmers, support for water users associations (IWUAs) and extension staff, production improvement through enhanced water productivity, use of appropriate agronomic practices, improved enterprise profitability, and establishment of an interactive database for information sharing and networking among stakeholders. Manuals were produced based on a methodology of participatory rapid diagnosis and planning (van der Schans and Lemperiere, 2006). Ten pilot schemes were identified and project activities were carried out between 2003 and 2006. Project funding was extremely limited, with IPIA funding averaging less than $3,000 per site, while GOK and local contributions were estimated at up to $90,000 per site.

The project resulted in significant yields increases through most of the schemes, particularly at Mwea, Kibirigwi, Naro Moru, and Hewani. Secondary data from Hewani indicated a three-fold increase in yield, while yield more than doubled in a Kibirigwi scheme with improved water application. In Mwea where there had been no IWUA, a well-trained management committee was established after several sensitization meetings were held. The National Irrigation Board (NIB), which had previously been rejected by the farmers due to its top-down approach, has now been accepted as the water service provider. Farmers now benefit from the services the government and other stakeholders are able to offer. Infrastructure improvements have been undertaken resulting in more equitable distribution of water, among other benefits. While some farmers have enjoyed an increase of 750 to 1,250 kg/ha due to proper use of fertilizer and other crop husbandry techniques, in previously-contentious Block W3, the increase is more than 100%. Some farmers who harvested less than 25 bags/ha reported yields of more than 62.5 bags/ha due to assured provision of water brought about by their IWUA. Farmers now receive water in a one- to two-week rotation to avoid crop losses.

Another improvement was growing of more than one crop per year, especially in the Mwea scheme where one rice crop was traditionally grown and the land left fallow the rest of the year. Farmers are now able to grow other crops immediately after harvesting the rice crop; these include soya beans, green gram (a leguminous plant also known as mung bean), and short-season corn. Other crops grown in the scheme are sunflower, French beans, passion fruit, tomatoes, and other leguminous and horticultural crops. The same trend was found in Naro Moru and Kibirigwi schemes where new crops were introduced to increase farm profitability through improved plot use.

In Southwest Kano, the IPIA initiative was timely because it coincided with the planned revival of the scheme after five years of abandonment. The project has contributed to reduced canal siltation and unauthorized water diversions through training farmers and extension staff on water management. The training included land leveling to improve on-plot water use efficiency. While other stakeholders contributed to improved plot use through training on agronomic practices, IPIA facilitated the formation of an operational water users association in the scheme.

The results of this modest project have been surprisingly good. After being a relatively neglected sector in Kenya for many years, irrigation is now picking up. Farmers are receptive to the assistance when their voices are heard, as has been the approach of the IPIA project. Farmers are open to new markets and realize that cooperation over water allocation is essential for sustainable improvements in income.

MICRO-IRRIGATION TECHNOLOGIES

Treadle Pumps

KickStart, formerly known as ApproTEC, is a non-profit social enterprise, which for the past 15 years has produced a manual irrigation pump and other products that have been marketed to smallholders in Kenya and other SSA countries. The design of the pump has been continuously upgraded. A very efficient pressure pump has been developed: it allows two people working eight hours per day to irrigate nearly one hectare from a shallow water source. The maximum suction lift of the pump is 7 m and the maximum total pumping head is 14 m. As of 2006, KickStart had sold over 66,000 of its MoneyMaker line of pumps and created over 44,000 successful family enterprises generating over $47 million in annual profits. This novel approach to irrigation now accounts for over 0.5% of Kenya’s gross national product.

This success story has been closely followed by the international community, as well as other non-profit organizations. The key to the success in Kenya appears to be the marketing and the national distribution network. The pumps are widely advertised in local media, and a substantial amount of the KickStart budget goes to advertising. The pumps are widely available through a network of hardware stores throughout the country. KickStart has been firm in its conviction that serious farmers can find the resources to purchase the $95 pump, another key to the success. Giving away free pumps, as has been tried by various aid agencies, is not a successful approach because it does not discriminate the serious farmers prepared to produce crops for the market.

KickStart has recently introduced a Chinese-manufactured version of the treadle pump, produced at considerable cost savings compared to the locally produced version, with a strategy of covering more of the promotion costs from sales revenues. It has also introduced the MoneyMaker hip pump which is sold at $35 and is capable of irrigating about one-third ha.

Over the next three years, KickStart plans to expand into three more countries from their current operations in Kenya, Tanzania, and Mali. They expect to sell more than 125,000 pumps and create over 80,000 new irrigation businesses. They plan to introduce new and lower cost technologies, extend their marketing reach, and introduce a financing program to help farmers buy pumps. They are expanding their sales to other non-profit organizations, and continue to encourage the non-profits to adopt the proven KickStart model.

Low-Head Drip Irrigation Kits

Low-head drip irrigation systems were introduced in Kenya in the late 1980s. The earliest were supplied by missionaries but had limited impact (Sijali and Okumu, 2003). In 1996, the Kenya

Agricultural Research Institute (KARI) linked with Chapin, a U.S. manufacturer of drip irrigation equipment. Chapin supplied the kits, which were assembled and distributed locally through KARI. The kits are of various sizes. The smallest is the bucket kit consisting of a 20-liter bucket, an inline screen filter, PVC connector and header pipes, and four or more rows of conventional drip irrigation lines. The innovation of low head and good uniformity created a kit that was affordable and attractive to users, particularly for kitchen gardens. Tests of emission uniformity (EU) for 0% slope, 1.0 m head and 15 m lateral length have shown EU up to 90% depending on type of drip tape (Ngigi, 2006b). Larger kits, with storage ranging from 200 to 2,500 liters or more and drip lines covering 75-1,000 m^2 moved the farmer to a commercial producer. Various crops are successfully grown with the kits, including traditional vegetable crops such as green beans, tomatoes, cabbage as well as irrigated maize and baby corn.

The early approach was to import the equipment in container lots with the kits assembled and distributed by KARI. The bucket kits were marketed at $10-15. Demonstration farms with knowledgeable staff trained and sold kits to interested farmers. Demonstrations also were conducted at agricultural fairs around Kenya with some media coverage. Over the first ten years, KARI sold 15,000 units despite the lack of a mass marketing approach, national dealer network, or technical support program. KARI is in the process of transferring distribution to the private sector.

Stephen Ngigi recognized the opportunity to put together drip kits made from locally available parts, including drip tubing manufactured in Kenya. This was marketed as the Dream Kit, available in three sizes. Between 2002 and 2005, more than 200 drum/mini-tank (200 liter) kits, 500 jerrican (40-100 liter) kits, and 800 bucket (20 liter) kits were sold without a mass marketing campaign or a national distribution network (Ngigi, 2006b).

Little work has been done to measure the impact of drip kits. A stakeholders' workshop was conducted in 2000, which obtained feedback from users of the kits (Winrock, 2000). This workshop identified minor problems with clogging and similar problems. It was reported that many kits distributed freely by intermediaries were abandoned. Where users have been convinced of the utility of the kits and purchased them themselves, the utilization rate is much higher. One study showed that gross margins realized from the sale of tomatoes and other high-value vegetables amounted to $60, $380 and $1090 from the 20 liter bucket kit, the 200 liter drum kit and a 1000 liter kit serving 500 m^2, respectively (Nyakwara et al., undated).

In follow-up evaluations by KARI in the Northern Rift Valley and in Eastern Kenya (KARI, 2003), it was found that the performance of the kits was good when used to grow both food and income generating crops for the market. In drier areas where boreholes have been developed for women's groups, the most suitable technology was the larger kit covering 2,500 m^2. At one site women hand watered outside the area of the drip kit in order to extend production. A drawback of the drip technology was the limited availability. The study found that drip irrigation technology needs to be extended together with rainwater harvesting and pumping technologies. Utilization of the drip irrigation kits in conjunction with treadle pumps and/or rainwater harvesting ponds is an attractive option for farmers, although the pressure treadle pump is usually used to irrigate crops directly.

SMALLHOLDER FARMERS OUTGROWERS PROGRAM

Homegrown, a group company of Flamingo Holdings, is a Kenyan company that produces cut flowers and vegetables for the European market. They have an outgrower program that works with over 600 outgrowers producing green beans and other crops in 11 regions around the country, including Naro Moro, Thika, and Machakos.

In Machakos, Homegrown works with 16 farmer groups, with 10-15 farmers per group. They produce fine and extra fine green beans, courgettes (zucchini), and sugar snap peas. The farmers are paid Ksh. 45 per kg ($0.65 per kg) for fine grade beans. The fine quality must be less than 8 mm diameter, and extra fine less than 6 mm. Crops are harvested in the morning, cooled at the collection sites, transported in the evening, and placed on supermarket shelves within 48 hours of picking.

Crops are produced for four or five supermarket chains in the United Kingdom (UK) which require the outgrowers to meet international quality and farm worker safety standards. Farmers are provided spraying equipment and training in safety procedures and are required to rotate crops and fallow bean fields for 6 months. Farmers are required not to spray during the period prior to harvest, with strict no-spray periods ranging between one and seven or more days depending on the type of pesticide used. Homegrown has a tracking system that can track shipments back to the individual farmer or at least to the farmer group. Also, farmers are provided with seeds according to what they can produce based on water availability and demand. One of the standards is that the farmers must have a permit for irrigation water.

Homegrown's strategy is to grow in various climatic zones so that crops are planted every week and harvested throughout the demand period. Diversifying the supply of produce from different regions minimizes the risk that Homegrown will be unable to provide the UK markets with their expected needs. This is important as water availability (and crop production) varies across the regions according to time of year. Demand by the supermarkets is particularly high in the winter months when European farmers are not producing. Homegrown has negotiated with the UK markets to purchase the crops grown in Kenya year-round, ensuring a more regular income for growers during the European summer months. This is an incentive to keep farmers supplying to Homegrown even when demand is high and “suitcase exporters” offer higher prices. Those farmers who sell outside the Homegrown network and reduce the agreed upon supply to UK markets, can be penalized (through reductions in purchases) when demand is generally low but when Homegrown is able to by produce due to their guaranteed market.

Some of the outgrowers use drip or sprinklers while others use furrow irrigation, diverting from spring fed streams and applying water from furrows to individual plants with hose pipes or buckets. Most farmers are in a water short situation, and may have a rotation system, each farmer getting water two days a week or less. Low-head drip has the following advantages for these farmers:

- Time and water saving in irrigating.
- Evenly spaced plants resulting in higher plant population per unit area.

- Improved uniformity of plants resulting in higher quality product.
- Option to fertilize through irrigation lines.
- Drip systems can be removed during fallow periods and used in other fields.

While air freight limits the number of crops, other crops suited to smallholders, such as mangoes and avocados, have started to be exported to Europe via ship. The potential advantages to farmers in terms of increased income are huge, especially in comparison to producing for the local market.

CONCLUSIONS

Farmers who have access to seasonal water runoff can improve production with rainwater harvesting technologies. In some areas of Kenya, farmers have shown high adoption rates of farm ponds and other rainwater harvesting technologies. Rainwater harvesting provides an increased level of drought protection, and it allows more flexibility in market timing for those farmers producing market crops.

Public sector investment in irrigation development has been minimal in Kenya since at least the 1980s. Many existing schemes have languished without technical and other assistance from government and other sources. The IPIA project approach has shown that in many cases modest investments and technical support can measurably improve the performance of these schemes. Efforts to encourage farmers to diagnose constraints affecting their irrigation schemes, plan and carry out improvements, strengthen farmer organizations to collect operation and maintenance (O&M) funds, improve water distribution, and market produce have been shown to be readily accepted by farmers.

Micro-irrigation technologies, such as treadle pumps and low-head drip kits, provide farmers with low cost methods of improving water management. Farmers who previously lifted water with buckets and irrigated with water cans respond readily to these labor saving technologies. Farmers who have no previous experience with irrigation or who have no experience with producing and marketing high-value crops may not respond so readily. The establishment of training and demonstration centers would assist farmers to make the transition from subsistence to commercial producer.

Farmers are expanding production for the local market and participating in export opportunities. Labor intensive crops such as green beans, are excellent crops for smallholders. In order to meet quality standards, exporters have established systems and trained smallholders in pest management, pesticide handling and safety, and improved agronomic practices. The grail for smallholders—the export of high-valued crops—remains elusive except to a small number of farmers, but valuable experience about producing for the European market is being gained. In order to expand the pool of qualified farmers, programs need to be developed to train and organize groups of farmers so that they can successfully work with exporters.

REFERENCES

Ali, Aktar, Theib Oweis, Mohammad Rashid, Sobhi El-Naggar and Atef Abdul Aal, "Water Harvesting Option in the Drylands at Different Spatial Scales," Land Use and Water Resources Research, Vol. 7, http://www.luwrr.com, 2007.

Blank, Herbert G., Clifford M. Mutero and Hammond Murrray-Rust, editors, "The Changing Face of Irrigation in Kenya: Opportunities for Anticipating Change in Eastern and Southern Africa, International Water Management Institute, Colombo, Sri Lanka, 2002.

CIA, Factbook, https://www.cia.gov/cia/publications/factbook/print/ke.html, Washington, DC. 2007.

Earthtrends. World Resources Institute http://earthtrends.wri.org/text/agriculture-food/country-profile-96.html, 2006.

Flamingo Holdings. https://www.flamingoholdings.com, 2007.

Gichuki, Francis N. and Herbert G. Blank, "Water Conflicts in the Upper Ewaso Ng'iro Basin: Causes, Impacts and Management Strategies, unpublished, presented at 2nd International Conference on Irrigation and Drainage, Water for a Sustainable World–Limited Supplies and Expanding Demand, USCID, Phoenix, 2003.

KARI Irrigation and Drainage Programme, "Up-scaling low cost drip irrigation technology in Kenya (activity 02070111): Technical report on drip irrigation activities in Rift Valley Province," Ministry of Agriculture, 2003.

Malesu, Maimbo M., Joseph K. Sang, Orodi J. Odhiambo, Alex R. Oduor and Meshack Nyabenge, "Rainwater Harvesting Innovations in Response to Water Scarcity, the Lare Experience, Technical Manual No. 5, World Agroforestry Centre (ICRAF), Nairobi, Kenya, 2006.

Mati, B. M. and F.W.T. Penning de Vries "Bright Spots on Technology-Driven Change in Smallholder Irrigation: Case Studies from Kenya" in Penning de Vries, F. W. T. (Ed). Bright Spots Demonstrate Community Successes in African Agriculture. Working Paper 102. Colombo, Sri Lanka: International Water Management Institute, 2005.

Mwarasomba, Lincoln I., George M. Ndegwa and Maureen K. Nyang'wara, "Evaluation of the Project on Improving the Performance of Irrigation in Kenya," KARI, IWMI, KickStart, Nairobi, 2006.

Nyakwara, Z.A., D.W. Kilambya and S.M. Nabwile, "Social and Financial Evaluation of the Low Head Drip Irrigation Systems for Small Scale Farmers in Moiben Division, Uasin Gishu District," Socio Economics section, NARL, Kenya Agricultural Research Institute, Ministry of Agriculture, undated.

Ngigi, Stephen N. "Rainwater Harvesting for Improved Food Security, Promising Technologies in the Greater Horn of Africa" Kenya Rainfall Association, Greater Horn of Africa Rainwater Partnership, USAID, Nairobi, Kenya, 2003.

Ngigi, Stephen N., "Hydrological Impacts of Land Use Changes, Water Resources Management and Socio-economic Development of Upper Ewaso Ng'iro River Basin in Kenya" Dissertation submitted in fulfillment of PhD, UNESCO-IHE/Delft University of Technology, Taylor & Francis Group plc, London, UK, 2006a.

Ngigi, Stephen N., "Technical Evaluation and Development of Low-Head Drip Irrigation Systems in Kenya" Department of Environmental and Biosystems Engineering, University of Nairobi, Nairobi, Kenya, 2006b.

Sijali, I.V. and R. Okumu, "Low Cost Drip Irrigation Technologies for Sustainable Dryland Agriculture in Kenya. In "Proceedings of the Symposium and Workshop on Water Conservation Technologies for Sustainable Dryland Agriculture in Sub-Saharan Africa," Bloemfontein, South Africa. ISBN 1-86849-275-3, 2003.

van der Schans, Martin L. and Philippe Lemperiere, "Manual Participatory Rapid Diagnosis and Action Planning for Irrigated Agricultural Systems (PRDA)", International Programme for Technology and Research in Irrigation and Drainage, IWMI, FAO, Rome, 2006.

Winrock International, "Proceedings of Stakeholders Workshop on Low-Head Drip Irrigation Technologies in Kenya, Nairobi, Kenya, 2000.

IMPACTS OF CHANGING RICE IRRIGATION PRACTICES ON THE SHALLOW AQUIFER OF NASUNOGAHARA BASIN, JAPAN

Ali Elhassan[1]
Akira Goto [2]
Masakazu Mizutani [3]

ABSTRACT

The challenge for water resources planners is how best to manage the surface water and groundwater resources of a region to prolong their usefulness for present and future generations. This study was carried out in Nasunogahara Basin Tochigi Prefecture, Japan to evaluate the effect of changing rice crop irrigation practices on managing the use of water from the shallow aquifer of the area. The basin is an alluvial fan where paddy fields occupy 40% of the area. 66% of these paddy fields are irrigated by groundwater and are located in the southern part of the basin. The current practice is to carry out rice transplanting and land preparation, which is a high demand period for water, in a short period of 15 days. This short period usually starts in the middle of April and lasts until the beginning of May with the highest water demand is at the end of April and beginning of May.

In the early 1990s a trend of lowering in the groundwater table and drying up of the natural springs was observed in the basin. The reasons for this trend are suspected to be low precipitation and the influences of various new developments for residential or industrial land use in the northern part of the basin. This trend and the relatively short duration of the high water demand period caused severe groundwater shortages during the transplanting period in the basin.

An integrated surface water- groundwater model was developed as a tool for management of regional groundwater resources and used to examine the effect of prolonging the high demand period. The model simulated the effects of two longer periods of transplanting and land preparation, 30 and 60 days. The simulation results showed that extending the high demand period eased the groundwater shortage significantly. There are no major differences between the effects of the two periods, 30 and 60 days, in improving the water supply. Present institutional and economic constraints make the 60-day alternative impractical.

INTRODUCTION

Substantial increase in water demand for municipal, agricultural and industrial uses, created primarily by rapid population growth, makes the optimal joint operation of surface water and groundwater supplies attractive (Basagaoglu and Marino, 1999). With continued population

[1] Water Resources Engineer, New Mexico Interstate Stream Commission, P.O. Box 25102, Santa Fe, New Mexico 87504-5102
[2] Professor, Dept. of Environmental Engineering, Faculty of Agriculture, Utsunomiya University
Mine machi 350, Utsunomiya City, Tochigi 321-8505, Japan
[3] Professor, Dept. of Environmental Engineering, Faculty of Agriculture, Utsunomiya University
Mine machi 350, Utsunomiya City, Tochigi 321-8505, Japan

increases and economic development in many parts of the world, the stresses imposed on water resources consequently increase, resulting in undesirable impacts on both surface and groundwater systems. The challenge is how best to manage the interacting surface and groundwater resources of a region to prolong their usefulness for present and future generations. This study was carried out in Nasunogahara Basin Tochigi Prefecture, Japan to evaluate the effect of changing rice crop irrigation practices on managing the use of water from the shallow aquifer of the area. The basin is an alluvial fan where paddy fields occupy 40% of the area. The current practice is to carry out rice transplanting and land preparation, which is a high demand period for water, in a short period of 15 days. This short period starts in mid April and lasts until the beginning of May with the peak of water demand is at the end of April and beginning of May. In the early 1990s a trend of lowering in the groundwater table and drying up of the natural springs was observed in the basin. The reasons for this trend are suspected to be low precipitation and the influences of various new developments for residential or industrial land use in the northern part of the basin. This trend and the relatively short duration of the high water demand period caused severe groundwater shortages during the transplanting period in the basin.

In this study an integrated surface water- groundwater model was developed as a tool for management of regional groundwater resources in the basin and used to examine the effect of prolonging the high irrigation demand period. The model simulated the effects of two longer periods of transplanting and land preparation, 30 and 60 days. The simulation results showed that extending the high demand period alleviated the groundwater shortage.

OUTLINE OF NASUNOGAHARA BASIN

Nasunogahara Basin is an alluvial fan with a total area of about 40,000 ha. The basin is situated in the northern part of Tochigi Prefecture, Japan. The total paddy field area of the fan is 15,000 ha, out of which around two thirds are irrigated by groundwater. The paddy fields irrigated by groundwater are located in the lower part of the fan where abundant shallow groundwater is available. On the other hand Nasunogahara Canals Irrigation Scheme supplies irrigation water for the paddy fields in the upper area of the fan.

Nasunogahara Basin is surrounded by Hoki River to the west and Naka River to the east. Between these two rivers, Sabi River had mainly developed the fan (Figure 1). Sabi River and its tributary Kuma River usually have no water in their riverbeds in the upper area of their streams. Runoff water of these rivers flowing down from the mountains disappears from the riverbed surfaces to the subsurface because of the high permeability rates of the riverbeds' coarse gravel formation. River water can be seen in the upper part of the two rivers only after big storms. A part of the river's water that flows under the ground, appears again to their riverbeds in the lower part and the rest is believed to recharge the groundwater along the river. The mean annual rainfall of the area is about 1500-mm. Nasunogahara canal irrigation system (Figure 1) has an important role in the hydrologic regime of the fan. It supplies stable water, which is diverted from Naka River, for irrigating the paddy fields in the upper area of the fan. The water infiltrating from these paddy fields is an important source of groundwater recharge.

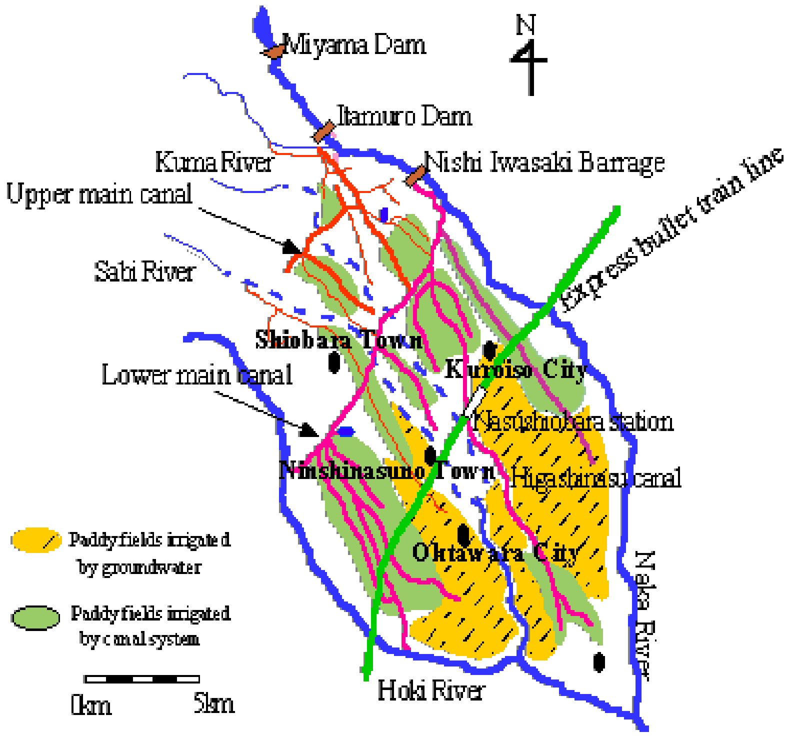


Figure 1. Outline of Nasunogahara alluvial fan, Tochigi Prefecture, Japan, and its irrigation system

On the other hand, in the lower area of the fan, water pumped from the unconfined aquifer is the major source of irrigation. The irrigation period for paddy fields in the area usually starts in April and ends in August, which is the rice-cropping season.

MODEL DEVELOPMENT

The integrated model simulated comprehensively the hydrologic processes in Nasunogahara Basin. The recharge processes, which were simulated in this model, include recharge from precipitation, infiltration from applied irrigation water and recharge from Sabi River's underflow. The discharge processes include pumping of groundwater and discharge by springs (Elhassan, et al., 2001).

Groundwater Flow Model

The groundwater flow model was developed assuming that the aquifer is single-layered, isotropic and heterogeneous. The flow was assumed to be transient and two-dimensional. The partial differential equation that governs the flow in the aquifer is Boussinesq equation for the two-dimensional, transient flow in an unconfined aquifer (Anderson and Woessner, 1991):

$$\frac{\partial}{\partial x}\left(kh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(kh\frac{\partial h}{\partial y}\right)=S_y\frac{\partial h}{\partial t}-R \qquad (1)$$

where h is the saturated thickness of the aquifer (m), k is the hydraulic conductivity (m.d^{-1}), x and y are the spatial coordinates, S_y is the specific yield of the unconfined aquifer, t is time (d), and R is the source-sink term (m.d^{-1}).

Equation (1) was solved using an implicit finite difference scheme namely the Crank-Nicolson scheme and Gauss-Seidel iteration technique (Wang and Anderson, 1982).

Combining Tank Model with the Groundwater Flow Model

Tank model, which is a conceptual rainfall-runoff model, is one of the applicable and widely used rainfall-runoff models in Japan (Sugawara et al., 1974). Goto and Sawata (1999) modified the ordinary tank model so as to express the property of paddy field irrigation in an alluvial fan and they used it to assess the water balance in Nasunogahara alluvial fan, Japan. In the modified tank model, the upper tanks, which represent the hydrologic processes on the ground surface, consist of a paddy field tank and non-paddy field tanks. The upper part of the modified tank model was combined with the groundwater model to calculate groundwater recharge to the shallow aquifer, by different recharge sources, as well as water pumped from the aquifer for irrigation as seen in Figure 2.

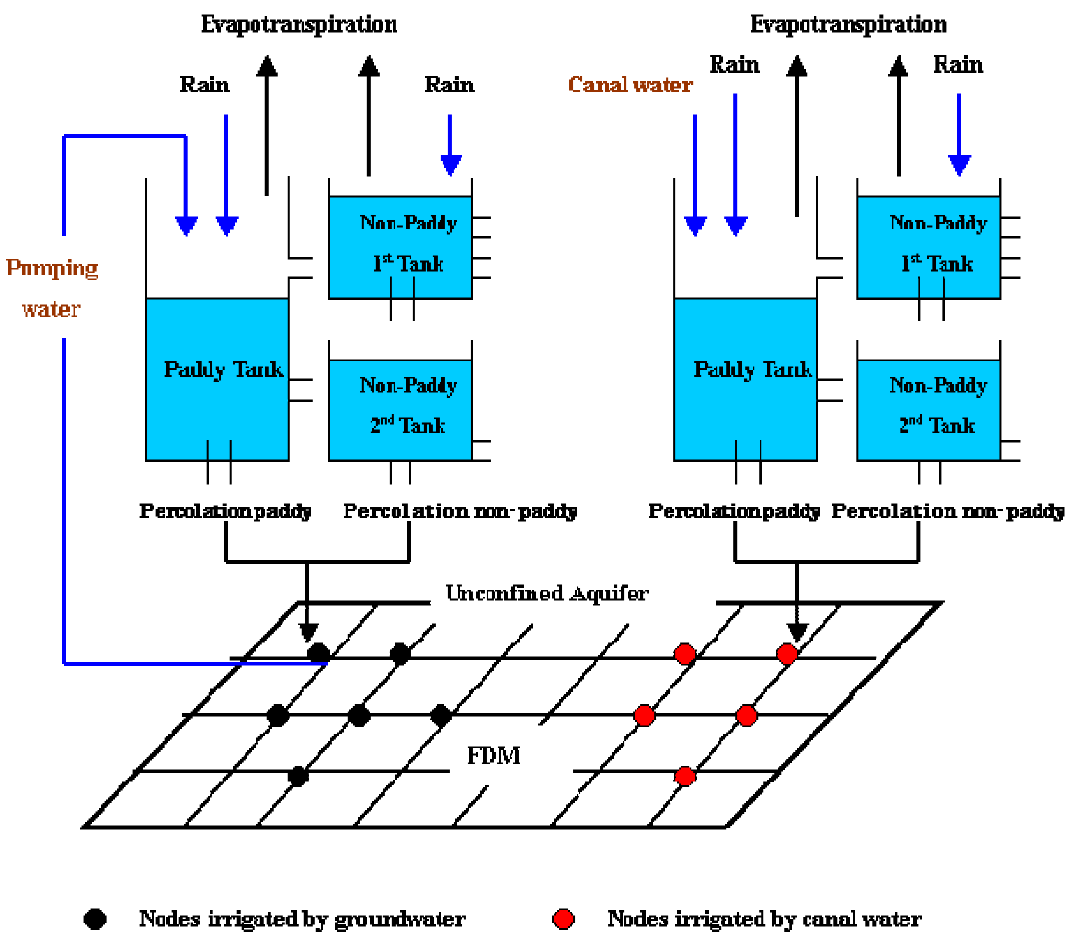


Figure 2. Combination of the modified tank model with the groundwater flow model

Calculation of groundwater recharge

The modified tank model calculated the percolation rate from the upper tanks to the shallow aquifer tank from both paddy field and non paddy field areas separately for irrigation and non-irrigation periods (Fig. 2). Percolated water from the ground surface tanks directly recharges the shallow groundwater. Furthermore, in the tank calculation percolation rates from paddy fields irrigated by groundwater were calculated separately from those irrigated by canal water. From the maps of beneficiary areas of Nasunogahara irrigation system, paddy fields were distinguished based on their source of irrigation water to paddy fields irrigated by groundwater, which are located mainly in the lower part of the fan and receive pumping water only, and paddy fields irrigated by canal water, which are located in the upper part of the basin where no pumping is practiced in those paddy fields.

Calculation of groundwater discharge by pumping

In many regions it is difficult to estimate the exact amount of distributed groundwater pumping from the aquifer, because exact locations of many users are unknown and they are pumping water by using small portable pumps without keeping water extraction records. Therefore, in this model the modified tank model was also used to calculate the amount of groundwater withdrawals from the aquifer.

To calculate the amount of water pumped, a certain ponding depth was assumed to exist in the paddy field tank during the irrigation period. The value of the ponding depth was estimated based on the agricultural practices of the area. Pumping from the shallow aquifer starts when the water level in the paddy tank becomes less than the assumed value and pumping stops when the ponding depth in the paddy tank reaches the assumed value.

MODEL CALIBRATION AND VALIDATION

The model was applied to Nasunogahara Basin to describe the seasonal variation of the groundwater table elevation throughout the fan, using a daily time step. The groundwater table elevations were calculated by adding the elevation of the upper surface of the impervious layer and the thickness of the water above the impervious layer (h) calculated by equation (1). A grid having a nodal spacing of 1-km divided the fan into 713 nodes, out of which 438 nodes are active nodes (Figure 3). Prescribed head boundaries were assigned along Hoki River and the lower part of Naka River (Figure 3). The upper part of Naka River and the boundaries between the mountainous area at the north-western part and the fan were treated as no-flow boundaries because of the presence of confining layers. A steady state water table configuration was computed and used as the initial conditions for the transient simulation.

Primary values of the groundwater flow model parameters and input data were obtained or estimated from existing records, topographic and hydro-geological maps and previous research studies.

In their research, Goto and Sawata applied the modified tank model to the area west of Kuma River in the alluvial fan in order to calculate runoff discharges to rivers in the area (Goto and

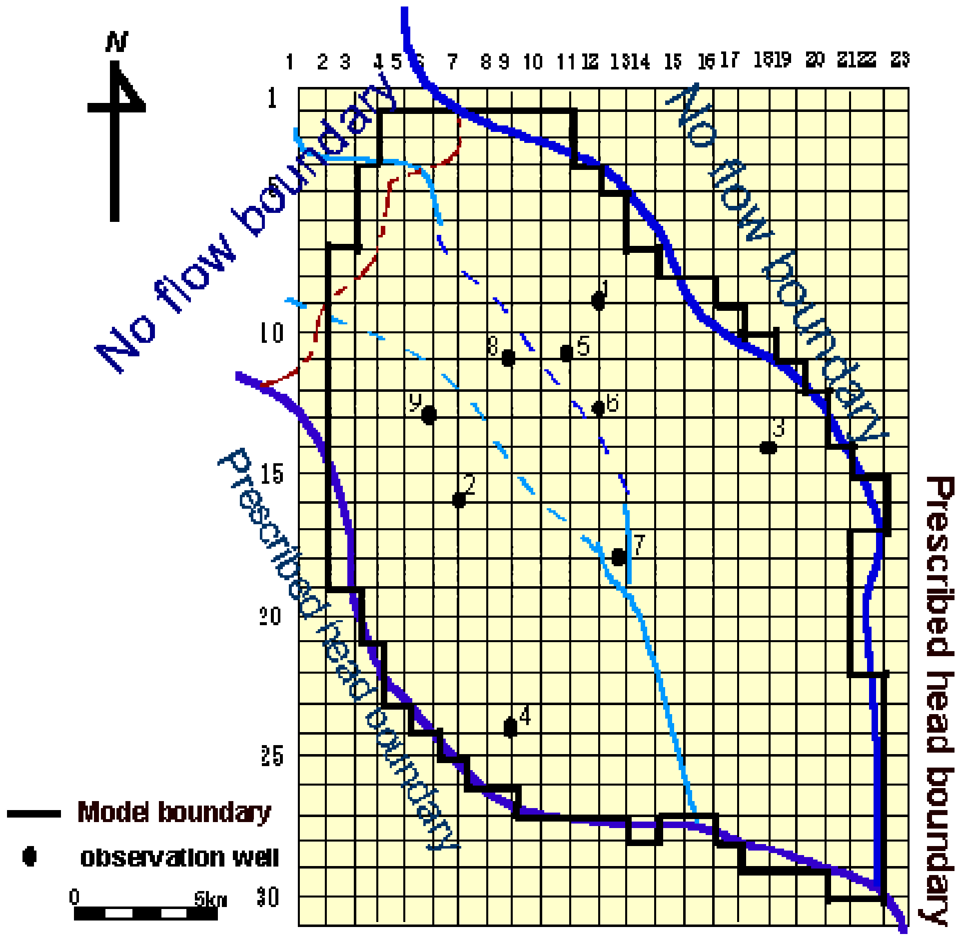


Figure 3. Groundwater model grid, boundary conditions and locations of observation wells

Sawata, 1999). Tank model parameters determined and input data used in their study were adjusted and used in this research where the area was simulated as one basin having a uniform set of parameters.

The calibration and validation of the transient two-dimensional groundwater flow model were based solely on the hydraulic-head distribution. Through trial and error calibration, groundwater model parameters, mainly *k* (355 ~ 650 m.d^{-1}) and *Sy* (0.07~0.15), prescribed head boundaries and areas of paddy fields irrigated by canal water and pumping in the tank calculation were adjusted to find the suitable set of parameters that makes the computed water table elevations agree satisfactorily with those observed in the field (Elhassan, et al, 2001).

The model was calibrated using daily water table elevation data from the nine observation wells shown in Fig. 3, for four years from 1991 to 1994. An independent set of data for 1998-1999 for only three wells, well 1, well 4 and well 9, was obtained and used to validate the calibrated model.

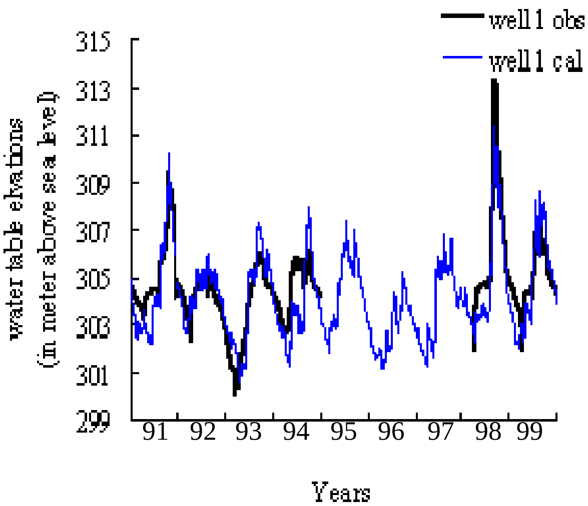


Figure 4. Comparison between calculated and observed water table elevations at observation well 1 (1991-1999)

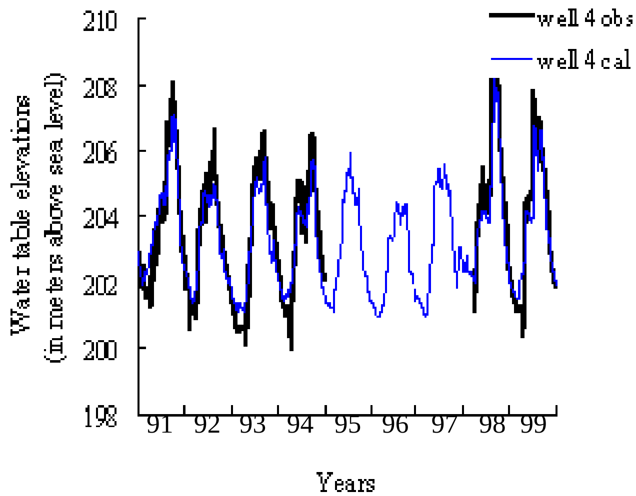


Figure 5. Comparison between calculated and observed water table elevations at observation well 4 (1991-1999)

Generally the comparisons between the calculated and observed water table elevations show a good correlation at most of the wells during the application period as can be seen in Figures 4 and 5. It indicates that the model is able to depict the seasonal variations in the water table elevations of the unconfined aquifer satisfactorily. It was noticed that the water table elevations in all observation wells rose during the irrigation period from April to August and dropped during the non-irrigation period. For detailed information about model structure, application and water balance of the area please refer to the paper titled: Effect of Conjunctive Use of Water for Paddy Field Irrigation on Groundwater Budget in an Alluvial Fan. (Elhassan, et al., 2003).

SIMULATION SCENARIOS OF DIFFERENT IRRIGATION PRACTICES

Japan is the only industrialized country whose agriculture is based on rice. Agriculture in Nasunogahara Basin is no exception where rice is the main crop. The irrigation period for paddy fields in the area usually starts in April and ends in August with the highest water demand being during the transplanting and land preparation. The current practice in the area is to carry out the transplanting and land preparation in a short period, 15 days, starting in the middle of April and lasting until the beginning of May. The highest demand period is at the end of April and beginning of May, which is a famous holiday in Japan known as the golden week. The reason for that is because farmers are part-time farmers who have permanent jobs other than rice farming; therefore they use these holidays to perform land preparation and transplanting activities.

In the early 1990s in Nasunogahara Basin, a trend of lowering in groundwater table and drying up of the natural springs has been observed. It has sometimes caused irrigation water shortages during the high demand season. Besides low precipitation, the influences of various developments for residential or industrial land use in the upper part are considered to be the reasons for the trend. This trend and short duration of high water demand caused severe groundwater shortages during the transplanting period in the basin, Figure 6.

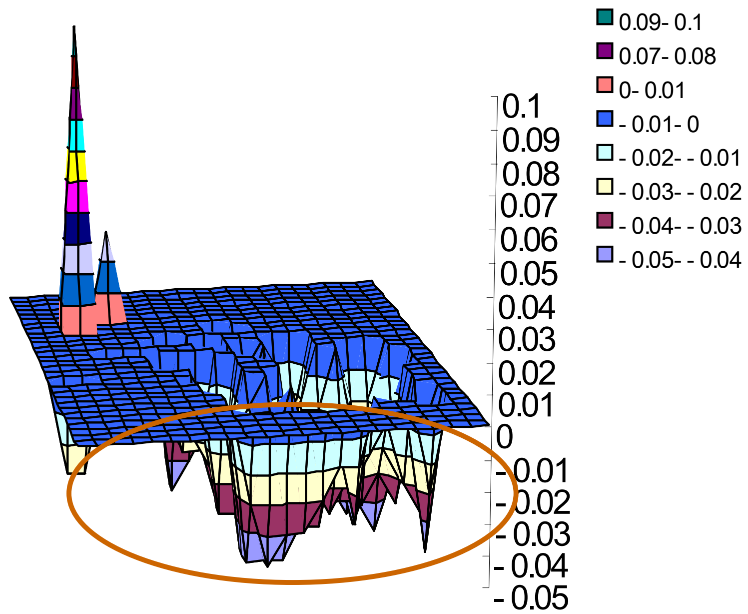


Figure 6. Distributed Source-Sink term ($m.d^{-1}$) on 15th of April 1993, excessive pumping at the beginning of irrigation season caused severe water shortage

The model was used to examine the effect of extending the length of the high demand period. The effect of two longer periods of transplanting and land preparation, 30 and 60 days, on shallow water supply was examined. The irrigation season was also lengthened so as to allow for the whole agricultural practices of rice farming to be completed. In the current model the irrigation season starts in mid-April and lasts until the end of August.

30-Day Transplanting Period Scenario:

For the 30-day scenario, the irrigation season starts at the beginning of April and ends at the end of September. Land preparations and transplanting period starts at the beginning of April and ends at the beginning of May. The simulation results showed that extending the high demand period to 30 days eased the groundwater shortage as indicated by the positive values of the source–sink term for that period (Figure 7).

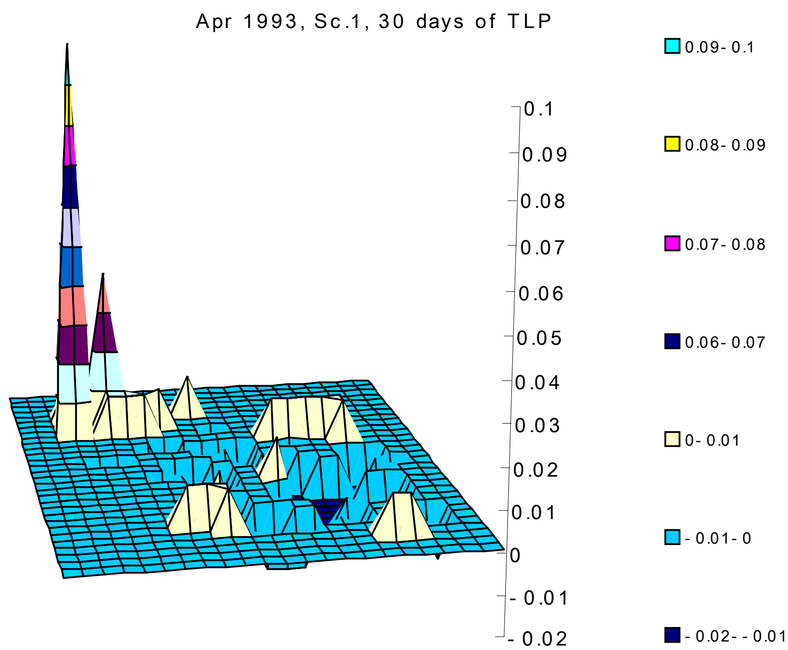


Figure 7. Simulated distributed Source-Sink term ($m.d^{-1}$) on 15th of April 1993, using a period of 30 days for transplanting and land preparations

60-Day Transplanting Period Scenario:

For the 60-Day scenario, irrigation commences at the end of March and ends at the beginning of October and the land preparations and transplanting period starts at the end of April and ends at the beginning of June. The simulation results showed that extending the high demand period to 60 days alleviated the groundwater shortage as indicated by the positive values of the source–sink term for that period (Figure 8). The practice of performing the land preparations and transplanting in 60 days was practiced in the area in the past. Although 60 days for transplanting and land preparation can alleviate the water shortage, this alternative is considered impractical. This is due to the present institutional and economic constraints mainly because the farmers are part-time farmers who have permanent jobs other than rice farming.

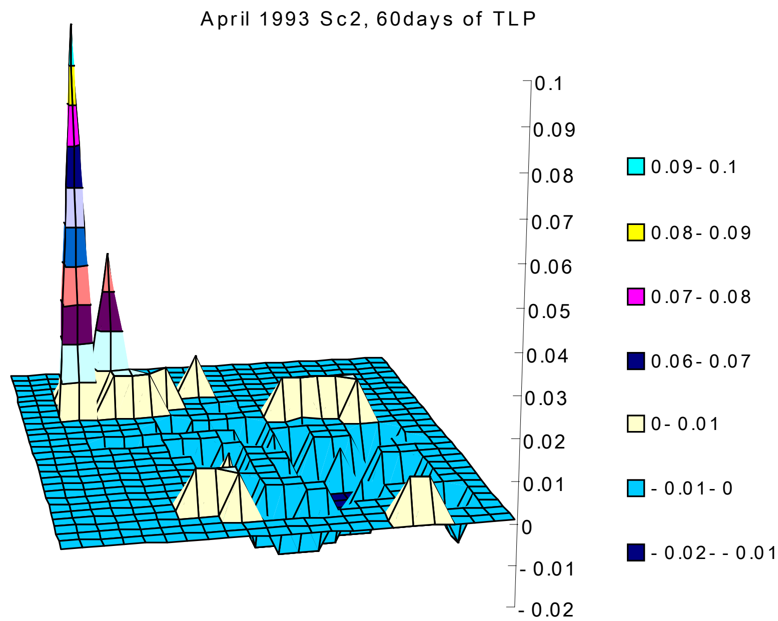


Figure 8. Simulated distributed Source-Sink term ($m.d^{-1}$) on 15th of April 1993, using a period of 60 days for transplanting and land preparations

CONCLUSION

An integrated surface water- groundwater model was applied to Nasunogahara alluvial fan, Japan. The model-calculated water table elevations during the application period show a fairly good correlation with field observation data. The model was able to simulate the daily changes in the water table elevations throughout the fan area; hence the model's ability to describe the actual behavior of the aquifer was confirmed. By using this model, hydrologic impacts on the shallow aquifer resulting from extending the length of the rice transplanting and land preparation period, which is a high demand period for water, were simulated and evaluated. Two scenarios were simulated:

30-Day Transplanting Period; and
60-Day Transplanting Period.

The simulation results showed that extending the high demand period alleviated the groundwater shortage. There are no major differences between the effects of the two periods, 30 and 60 days, in alleviating the water shortage. Present institutional and economic constraints make the 60-day alternative impractical; the 30-day option is preferable. It can be concluded that the model proved to be an effective tool for planners of the groundwater resources in alluvial fans. The model can assess the response of the water table to different hydrologic stresses resulting from changes in irrigation practices.

REFERENCES

Anderson, M. P., and W. W. Woessner. 1991. *Applied groundwater modeling*. Academic Press.
Basagaoglu, H., and M.A. Marino. 1999. Joint Management of surface and ground water supplies, *Groundwater*, Vol. 37, 214~ 222.

Elhassan, A. M., A. Goto, and M. Mizutani. 2003. Effect of Conjunctive Use of Water for Paddy Field Irrigation on Groundwater Budget in an Alluvial Fan, *Agricultural Engineering International: the CIGR Journal of Scientific Research and Development*. Manuscript LW 03 002. Vol. V.

Elhassan, A. M., A. Goto, and M. Mizutani. 2001. Combining a Tank Model with a Groundwater Model for Simulating Regional Groundwater Flow in an Alluvial Fan, *Trans. Of Japanese Society of Irrigation, Drainage and Reclamation Engineering, JSIDRE*. No. 215: 21~29.

Goto, A. and A. Sawata. 1999. Groundwater use for paddy field irrigation and its effects on groundwater recharge in an alluvial fan, In *Trans. 17th ICID congress*, 48 ~62. Granada, Spain.

Perkins, S. P., and M. Sophocleous. 1999. Development of a comprehensive watershed model applied to study stream yield under drought conditions, *Groundwater*, Vol. 37, 418~ 426.

Sugawara, M., Ozaki, E. Watanabe, I., and Y. Katsuyama. 1974. Tanks model and its application to Bird Creek, Wollombi Brook, Bikin River, Sanaga River and Nam Mune. *Research notes, National research center for disaster prevention*. Tokyo. No. 11: 1~ 64.

Takase, K. 1999. Environmental Issues. In *Advanced paddy field irrigation.* 341-365. Japanese Society of Irrigation, Drainage and Reclamation Engineering, JSIDRE. Shinzan-sha science and technology publishing Co.

Wang, H. F., and M. P. Anderson. 1995. *Introduction to groundwater modeling*. Academic Press.

DROUGHT PROTECTION FROM AN IN-LIEU GROUNDWATER BANKING PROGRAM

Owen E. Kubit, PE[1]
Richard M. Moss, PE[2]
John P. Roldan, PE[3]

ABSTRACT

The framework is provided for a drought preparedness plan (Drought Plan) for the Orange Cove Irrigation District (District) located in the Central Valley of California. The Drought Plan will improve water supply reliability for the District, which needs a firm water supply to support permanent plantings that cover over 90 percent of the District. The District uses a combination of surface and groundwater and has surplus surface water in some years, but the local geology is not favorable for direct recharge using ponding basins. The District therefore investigated several options for drought protection including water purchases, out-of-District groundwater banking, and in-lieu groundwater recharge in their own service area. In-lieu groundwater recharge was found to be the most economical alternative and would be under the full control of the District. Under the program, some District growers would be sold surplus surface waters at reduced rates, and this would allow groundwater levels to rise and groundwater storage to increase. In dry years, these growers would meet most or all of their demands with groundwater, and would transfer their surface water to areas with low groundwater yields. Details of the program were developed with considerable input from local growers through a public outreach program. A pilot program was outlined with the intention of testing the feasibility of the program on a smaller scale. Other topics discussed include incentives for growers to participate, groundwater level monitoring, project benefits and impacts, and project economics. The California Department of Water Resources funded development of the program.

INTRODUCTION

The Orange Cove Irrigation District (OCID or District) is an agricultural water district encompassing approximately 28,000 acres in the Central Valley of California. Growers in OCID are dependent on surface water and groundwater supplies. Some use groundwater exclusively while others use a combination of surface and ground water. Total average crops demands are roughly 80,000 acre-feet (AF) per year. Typically, about 32,000 AF of surface water and 48,000 AF of groundwater are used to meet this demand.

The District has a Class 1 Central Valley Project surface water contract with the United States Bureau of Reclamation. Although Class 1 water is classified as "firm" water, its delivery has

[1] Senior Engineer; Provost & Pritchard Engineering Group, Inc; 286 West Cromwell Ave, Fresno, CA 93711; okubit@ppeng.com
[2] Principal Engineer; Provost & Pritchard Engineering Group, Inc.; 286 West Cromwell Ave, Fresno, CA 93711; rmoss@ppeng.com
[3] Engineer-Manager; Orange Cove Irrigation District; 1130 Park Blvd, Orange Cove, CA, 93646; jrocid@sbcglobal.net

historically been reduced in some drought years. The District must rely on groundwater to augment surface supplies, and the groundwater supplies can be stressed in dry years when surface water deliveries are reduced. Although the District encompasses 28,000 acres, only about 9,000 acres has a sustainable groundwater supply (see Figure 1). In addition, permanent crops comprise over 90 percent of the cropped area, so the District has little flexibility in reducing their water needs during droughts without sustaining crop or tree loss. At this time, the District has no long-term agreements with other agencies for banking and/or exchange of water between wet and dry years, which places the District at risk of not being able to supply adequate water in a drought.

The District's distribution system was rehabilitated and expanded in the early 1990's to allow delivery to all District growers. However, some growers still decline some or all of their surface water allocation due to the lower prices and greater convenience of using groundwater. As a result, only about 32,000 AF of the District's 39,200 AF surface water entitlement is normally used. This practice is typically short sighted and uses resources that could be reserved for a dry year or, more importantly, during an extended drought in the future. OCID wants to encourage landowners to use all of their surface water so that groundwater storage can increase and be available during droughts. As a result, OCID developed an in-lieu groundwater banking program. The program encourages landowners to use surplus surface waters 'in-lieu' of groundwater. This reduces groundwater pumping, allows groundwater levels to rise, and increases groundwater storage for use in dry years. The development of this program was funded with a grant from the 2000 Local Groundwater Management Assistance Act (Assembly Bill 303) administered by the California Department of Water Resources.

This paper discusses the District's plan for an in-District groundwater-banking program, which will from hereon also be called the District's 'Drought Plan'. This paper provides background information on past efforts to develop the Drought Plan, and planned future efforts to implement the Drought Plan. The remainder of the paper discusses anticipated benefits and impacts from implementing the Drought Plan.

ALTERNATIVES FOR DROUGHT PROTECTION

OCID evaluated numerous alternatives for drought protection and water reliability, including unique and innovative programs to meet their specific needs and situation. Some alternatives for providing drought protection include: 1) water purchases; 2) groundwater banking outside of the District; and 3) in-District groundwater banking. All three of these options are discussed below.

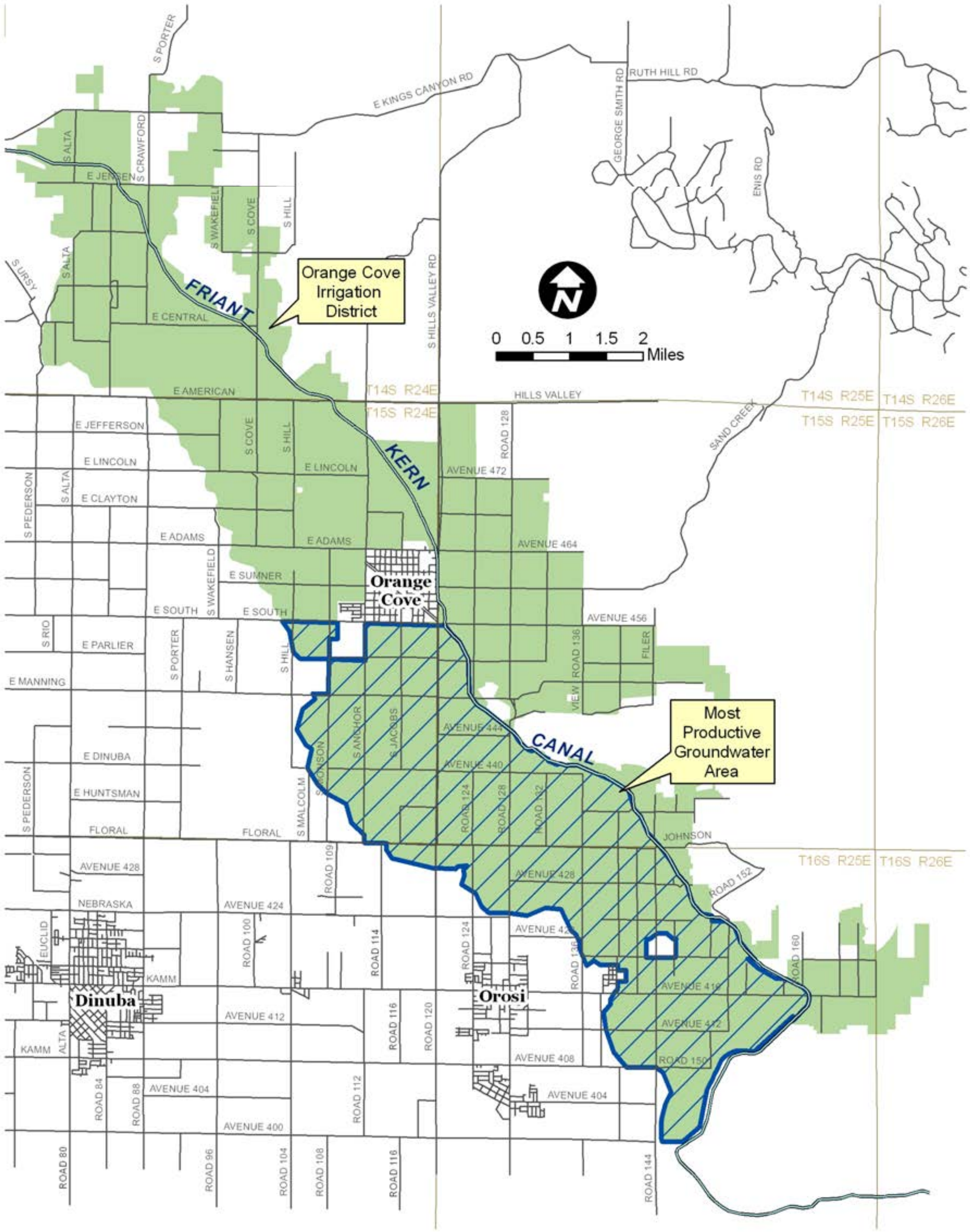


Figure 1. District Service Area including Most Productive Groundwater Area

Water Purchases

Water purchases are a common way for agencies to improve water reliability in dry years. Water markets are typically based on spot market pricing unless prearranged purchase plans or long-term agreements are in place. Dry year water supplies in California are estimated to cost about $100 to $500 per AF. These prices are considered high for agricultural uses, and open market water purchases will become increasingly more difficult for agriculture when placed in direct competition with urban users. Given the urban growth in the region and increasing regulatory uncertainty as to the availability of surface water, the pricing of future spot market water purchases is very likely to increase.

Groundwater Banking with Others

Groundwater banking outside of OCID is also a viable alternative. Typically, OCID would need to buy shares in a banking facility already owned and operated by another entity(ies). OCID would deliver water to the facility or entity for recharge during wet years, and retrieve the water as needed in dry years. Typical costs for “buying” into banking projects currently range from $150 to $300 per AF of retrieved water plus an upfront one-time capital expenditure of $500 to $1,500 per AF of retrieval capacity. Groundwater banking can provide a fairly firm water supply in dry years, and is considered much firmer than spot market water purchases. However, there is an element of risk relying on the facilities and programs owned by others even under the best-intentioned agreement. When extraction and conveyance facilities are in high demand at banking projects in dry years, even the best laid projects can be stressed to perform.

In-District Groundwater Banking

The use of in-District groundwater storage capacity is essentially a banking program within OCID. Under this scenario, the District would bank water by either actively recharging the groundwater basin or by providing surface water in-lieu of groundwater pumping. In both cases, there would be a net increase in the quantity of groundwater stored and available for future pumping by either the District or their water users. Few if any areas within OCID are conducive to direct groundwater recharge due to fine-grained surface soils. However, OCID could implement an in-lieu groundwater banking program. This would involve the use of surplus surface water ‘in-lieu’ of groundwater, which would allow groundwater levels to rise and increase groundwater storage for later use in droughts.

Since the program will only involve parties internal to the District it may be more economical than water purchases or banking agreements that ultimately offer some benefit to third parties, at the expense of the District. It also would provide greater assurance relative to future performance. In addition, no new facilities would need to be constructed to implement the program. As described later in this paper, this in-lieu groundwater banking program could be implemented for as low as $90/AF, which is considerably cheaper than water purchases or banking outside of OCID.

The balance of this paper focuses on the development of the in-lieu groundwater-banking program (Drought Plan). However, in order to have a diversified range of options for acquiring drought water, OCID plans to pursue all of the options described above to some degree.

DESCRIPTION OF IN-LIEU GROUNDWATER BANKING PROGRAM

This section provides a description of the in-lieu groundwater-banking program including incentives for landowners, administrative details, and a hypothetical example of Drought Plan operations.

Participation Requirements

Landowner participants would need to meet the following requirements:

- Uses surface water supplies on a routine basis, but does not typically use surface water to meet all crop demands;
- Located within the 9,000-acre "banking area" (most productive groundwater area);
- Willing to relinquish all or a portion of their surface water supply in dry years; and
- Be able to meet all, or at least a majority, of their crop water demands by groundwater pumping in dry years.

Incentives for Participants

The Drought Plan would require the voluntary participation from many landowners so sufficient incentives to encourage participation are crucial. As a result, a program was developed with input from local growers to ensure that the project benefits are sufficient and equitable. Developing appropriate incentives required a large portion of the time needed to develop the overall Drought Plan. Nevertheless, the monetary incentives and program costs discussed throughout this paper are preliminary and were developed during planning-level analysis. They may ultimately need to be revised based on actual costs and grower's ultimate reactions to the program.

Growers will be asked to participate in two phases: a banking phase and a recovery phase. These phases could be several years apart so it was necessary to develop a two part incentive program. During the banking phase growers will use surplus surface water in place of groundwater pumping. OCID first attempted to understand why some users do not use all of their surface water allocation. The primary reasons included:

- Surface water purchases are more expensive than groundwater pumping. The difference varies for each grower, but it is estimated that groundwater typically costs less than half of the cost for surface water (in areas with a sustainable groundwater supply, depth to groundwater ranges from about 10 to 60 feet);

- Groundwater pumping is more convenient than receiving surface water since the landowner has direct control over the timing and flowrate of pumping; and

- Surface water supplies are low in minerals, limiting water penetration in most soils in the District without the addition of amendments. Whereas the local groundwater contains higher levels of salts which aid in water penetration. The local groundwater also contains a high level of nitrogen that is beneficial to the crops and offsets the need to apply equivalent units of commercial fertilizer.

The District needs to offer the landowners sufficient incentives to overcome these obstacles. This will be achieved by subsidizing surplus surface water so it costs no more than groundwater pumping. Groundwater pumping costs are estimated to be about $20/AF and surface water presently costs about $60/AF. Therefore, all surface water above and beyond a grower's average annual usage would be sold to the grower for $20/AF (a $40/AF reduction).

During the recovery phase the growers would be paid $50/AF to relinquish their surface water supplies for that year. The grower profit would be the $50 payment minus the cost to pump groundwater (approximately $20), minus any additional costs they incur to participate, such as amendments or new facilities. The incentive needs to be large enough to convince growers that they will at least make a slight profit on the program and are not exposing themselves to any unnecessary risks.

To help participants evaluate the economics of the Drought Plan the District prepared a participant worksheet (Figure 2). The worksheet helps determine whether a grower has enough groundwater pumping capability to participate and estimates the financial incentives for the grower. A copy of the worksheet is included as Figure 2**.**

Groundwater Outflow Losses

To account for groundwater outflow the District would leave behind 5 percent of the banked water. Thus, for every 100 AF banked by a grower, the District will retrieve (ask the grower to reduce their future surface water use by) only 95 AF. Groundwater levels will be monitored with shallow observation wells during the pilot project to help determine whether other loss adjustments are necessary. Based on a preliminary hydrogeologic evaluation groundwater outflow is not expected to exceed 5 percent of banked supplies over the anticipated bank and retrieval operation cycle, but this needs to be confirmed and will depend on how long the water is banked.

Other banking projects provide 10 percent or more to account for losses. However, these projects differ because the losses account for conveyance seepage and evaporation, basin evaporation, and phreatophyte transpiration, which are not present in this project. In addition, such losses are sometimes used as partial payment for banking facility infrastructure, which are also not needed for this project.

Drought Preparedness Plan Pilot Project
Orange Cove Irrigation District
Participant Worksheet

1. Do you have enough groundwater pumping capacity to meet full crop demands?

			Sample Calculations
A.	Pumping Flowrate (gpm)?		300
B.	Number of acres served by pump?		30
C.	Maximum number of days per week that pump can be run?		5
D.	Maximum number of hours per day that pump can be run on run days?		24
E.	Estimated irrigation system water application efficiency?	%	75 %

Calculate Potential Average Daily Application Rate per Week (inches/day)

$$\frac{A \times 96.3 \times 24 \times C \times D}{B \times 43560 \times 7 \times 24} \times \frac{E}{100} = \frac{A \times C \times D \times E}{316{,}635 \times B} \; \frac{\text{inches}}{\text{day}} = \text{(1)} \quad 0.28$$

Is this enough to meet to meet your estimated peak crop water needs?

Citrus	0.25 inches/day
Tree fruit	0.40 inches/day
Grapes	0.30 inches/day

NOTE: IF THE CALCULATED POTENTIAL AVERAGE DAILY APPLICATION RATE PER WEEK IS NOT ENOUGH TO MEET YOUR PEAK CROP WATER REQUIREMENTS, THEN GROUNDWATER ALONE CANNOT BE USED AND THE USE OF OCID WATER OR OTHER WATER SUPPLIES WOULD BE REQUIRED.

2. What would be the additional energy cost to pump groundwater?
(Assuming that a groundwater pump is already used on the property.)

			Sample Calculations
F.	What is the pumping water depth in feet? (depth to static groundwater + pumping drawdown)		100
G.	What is the pumping plant mechanical efficiency (If unknown, use 65%)?	%	65 %
H.	What is your utility company's average charge per kW-hr under your plan?		$0.16

$$\text{Energy Cost per AF} = \frac{F \times A \times 0.746 \times 12.1 \times 449 \times H}{3960 \times G/100 \times A} = \frac{102.3 \times F \times H}{G} = \text{(2)} \quad \$25.19$$

3. If the use of amendments (e.g. gypsum, calcium, etc.) are required to use OCID surface water, then estimate requirement per acre-foot of OCID water.
1 AF = 325,900 gallons

Cost of amendment per AF of water (3) $5.00

4. Cost for additional surface water used under the Program should be equal to or less than the cost to pump water minus the cost of amendment used to run additional OCID surface water supplies.
(Energy Cost per AF (2) - Amendment Cost (3)) $20.19

5. Payment to relinquish surface water in drought should be greater than
(See Energy Cost per AF (2)) $25.19

I:\Clients\Orange Cove ID -1093\10930401\AB 303\Drought Plan\Participant Worksheet.xls

Figure 2. Participant Worksheet

Banking Limitations

The participants would be limited in the quantity of water they could bank and return in a given year. The total quantity banked by a participant should not exceed more than two (2) years worth of the participant's average annual use during a 5-year base period. This is to ensure that the landowner does not bank such a large quantity of water that OCID cannot retrieve it in a reasonable time or before it flows out of the District. The quantity of water returned in a drought should not exceed the grower's average annual surface water use.

Safety Net

Landowners will probably not participate unless they have a safety net to account for unforeseen problems. As a result, OCID will allow participants to buy back their water on an emergency basis or be relieved of their commitment under extenuating circumstances.

The participants will be able to buy back their water for the higher of: 1) the spot market price for the District to buy water plus 10 percent; or 2) the District's nominal cost to buy water plus the District's initial investment in the banking program (on a per acre-foot basis) plus 10 percent. Alternatively, the banking participant could temporarily be relieved of these penalties if they petition the District. This could be possible, for instance, if a grower's pump fails and they are not able to get replacement parts for several days or weeks. In addition, the participant could be permanently relieved of their contract if it can be shown that the groundwater they have banked has flowed out of the District or away from their property.

This safety net also protects the District from delinquent landowners. The District can impose these fees on landowners that refuse to relinquish their surface water in dry years. Without this clause, a landowner could bank water at District outlay and never choose to give the water back. This alternative clearly lays out the damages the District would suffer and increases the likelihood that the District would be kept whole financially.

Triggers for Implementation

OCID would probably declare a drought and implement the retrieval part of the program when their surface water allocations are 85 percent or less of their maximum CVP contract entitlement. An 85 percent allocation would correspond to 32,300 AF of surface water, which is the average surface water demand in OCID. Therefore, there should be demand for some of the banked water in a year with an 85 percent or lower surface water allocation.

Hypothetical Example

To further elucidate the details of the proposed Drought Plan a hypothetical example is provided below:

District Participating Grower Average Water Uses:

Total Demand: 200 AF
Surface Water: 100 AF
Groundwater: 100 AF

Under Wet Year of Pilot Program:

Total Demand: 200 AF
Surface Water: 150 AF
Groundwater: 50 AF

*50 AF of OCID supply would be sold to grower at approximately $20/AF ($40/AF reduction in cost).
*Total of $40/AF x 50AF = $2,000 incentive paid by OCID.
*Total of 200 AF could be "banked" over multiple wet years.

Under Dry Year of Pilot Program:

Total Demand: 200 AF
OCID Surface Supply to Participating Grower: 5 AF
Groundwater Pumped by Participating Grower: 195 AF

*OCID would pay $50/AF incentive on 100 AF (average annual use of surface water) = $5,000.
*OCID could only retrieve 95 percent of "banked supply." 5 percent of "banked supply" would be left in aquifer.

IMPLEMENTATION OF IN-LIEU GROUNDWATER BANKING PROGRAM

Drought Plan Simulation

The Drought Plan was simulated to estimate the long-term yield and benefits from the program. The simulation was based on the hydrology of the Friant Division of the Central Valley Project over the 30-year period of 1975 through 2004. This period includes some of the driest and wettest periods on record. The simulation is shown in Table 1. In the simulation the bank was limited to holding no more than 15,000 AF at any time. The simulation showed that over a 30-year period a cumulative total of 45,000 AF would have been banked, 30,000 AF would have been withdrawn, and 15,000 AF would still be in the bank at the end of the 30-year period.

Table 1. Simulation of Operations

YEAR	Water Year Supply[1] Class I	Class II	Put	Take[2]	Available for Take	Costs Put-$40/AF Take-$50/AF
1975	100%	59%	5,000	0	5,000	$200,000
1976	75%	0%	0	5,000	0	$250,000
1977	25%	0%	0	0	0	$0
1978	100%	100%	5,000	0	5,000	$200,000
1979	100%	63%	5,000	0	10,000	$200,000
1980	100%	100%	5,000	0	15,000	$200,000
1981	100%	6%	0	0	15,000	$0
1982	100%	100%	0	0	15,000	$0
1983	100%	100%	0	0	15,000	$0
1984	100%	50%	0	0	15,000	$0
1985	100%	14%	0	0	15,000	$0
1986	100%	100%	0	0	15,000	$0
1987	91%	0%	0	0	15,000	$0
1988	78%	0%	0	5,000	10,000	$250,000
1989	98%	0%	5,000	0	15,000	$200,000
1990	68%	0%	0	10,000	5,000	$500,000
1991	100%	0%	5,000	0	10,000	$200,000
1992	83%	0%	0	5,000	5,000	$250,000
1993	100%	90%	5,000	0	10,000	$200,000
1994	80%	0%	0	5,000	5,000	$250,000
1995	100%	100%	5,000	0	10,000	$200,000
1996	100%	58%	5,000	0	15,000	$200,000
1997	100%	30%	0	0	15,000	$0
1998	100%	10%	0	0	15,000	$0
1999	100%	20%	0	0	15,000	$0
2000	100%	17%	0	0	15,000	$0
2001	100%	5%	0	0	15,000	$0
2002	100%	8%	0	0	15,000	$0
2003	100%	5%	0	0	15,000	$0
2004	100%	18%	0	0	15,000	$0
Total			45,000	30,000		$3,300,000

Notes: 1 - Class I supplies are usually fully allocated in normal and wet years. Class II supplies are typically only allocated in years with above average precipitation or with significant carryover storage from the previous year.
2 - Take includes both losses and return water.

Limited Hydrogeologic Evaluation

The rate of groundwater movement under OCID was estimated to be about 500 feet/year. As a result, most banked water would require at least 5 to 10 years to flow out of the recoverable range. However, these estimates are only approximate since limited data was available on aquifer parameters. Information will be collected in a pilot program (described below) to help refine aquifer parameters values. Parameters of interest include specific yield and transmissivity to determine the storage capacity and groundwater outflow, respectively.

Groundwater depths in the southern portion of the District range from 30 to 70 feet. Assuming an average groundwater depth of 45 feet, and a specific yield of 0.04 in the sand and clay aquifer (based on the stratigraphy encountered during the recent installation of monitoring wells), then storage under a unit area of land would be (45 – 20 feet) x 0.04 = 1.0 feet. This would only equate to 9,000 AF of storage over the 9,000-acre sustainable groundwater area. This falls short of the District's goal to ultimately bank 15,000 AF of water.

Limited Financial Analysis

The Drought Plan is estimated to be the least expensive option for the District to firm up dry year water supplies. Costs are minimized since no new facilities need to be constructed and no fees are paid to outside entities. Fees are paid to local growers for their participation, but the monies stay within OCID and benefit the local farming economy.

The cost to pump groundwater in OCID is estimated to be about $20/AF. The cost for surface water deliveries is about $60/AF. So the District will need to subsidize the balance of $40 per acre-foot to encourage landowners to use more surface water. When retrieving water, the District would pay the participants $50/AF to relinquish their surface water. Thus, the cost per acre-foot of water banked and retrieved would be $40 plus $50 or a total of $90/AF. This represents a minimum cost, as it does not include administrative costs, consultant costs, or the loss of 5 percent of the banked water to account for groundwater outflow. In addition, it is possible that larger incentives will be needed to encourage sufficient participation from landowners or, if OCID so decides, to fund groundwater well improvements to enable more growers to participate.

Pilot Program

In order to evaluate the Drought Plan on a smaller scale, the District plans to implement a pilot project. The District has proposed their Service Area 9 for the pilot project. This area covers 3,345 acres and is located within the 9,000-acre most productive groundwater area (see Figure 1). The pilot project will allow OCID to evaluate the administrative aspects of the plan, effectiveness of the incentives, willingness of participants, appropriate contractual requirements, impacts to participant operations, and impacts to groundwater levels. The District would need to bank about 2,000 to 3,000 AF and operate the pilot program for several years to get enough data for a meaningful evaluation. The pilot project would be based initially on the concepts described in the previous sections.

PROJECT BENEFITS

Drought Protection

The primary benefit of the in-lieu groundwater banking program is an improvement in the District's dry-year water supply. Without an effective plan some growers may suffer from reduced yields or total crop losses during droughts. The Drought Plan will also provide dry year water at a considerably lower cost than other options such as water purchases and groundwater banking outside of OCID.

Financial Incentives for Landowners

The Drought Plan was developed with incentives to encourage landowner participation. In fact, most participants should realize some profits from participating. The financial benefits would be the price paid to relinquish their surface water (currently proposed at $50/AF) minus the costs to pump groundwater and costs for any necessary facility modifications or amendment applications. For most growers this should equate to a safe and financially positive arrangement.

The cost of the Drought Plan will probably be financed through slightly higher water fees charged to all surface water users. However, this will result in long-term savings since the District will not have to eventually buy dry-year water for exorbitant prices that would be passed on to the water users.

An additional benefit is that any money expended by the District would be kept local. Thus, the exchange of money would be kept within the boundaries of the District and would benefit the local water users and economy, and not an outside or distant entity.

Local Control

The in-lieu groundwater-banking program would remain under the control of OCID. As a result, they would not be dependent on outside agencies to store or retrieve water, or decisions by outside agencies to increase costs, suspend projects, or not renew contracts.

Reduced Pumping Costs

The Drought Plan will temporarily raise groundwater levels and reduce groundwater-pumping costs for participating landowners. While groundwater is being stored the local groundwater levels will be higher resulting in lower pumping lifts and pumping costs. In addition, OCID plans to leave 5 percent of the banked water in the aquifer to account for groundwater outflow. This amount left behind will also produce higher groundwater levels until this water eventually flows away from the District.

PROJECT IMPACTS

Environmental Concerns

The program will be developed and implemented so there are no significant environmental impacts including long-term and short-term groundwater overdraft. Specifically, additional groundwater pumping in drought years will not exceed the added groundwater storage (resulting from fuller utilization of surface supplies). No permits are known to be necessary to implement the program. Consideration would be given to the location of participating growers so as to minimize the potential for increasing well interference with neighboring wells from short-term higher intensity well usage.

Impacts to Banking Participants

Participating landowners could experience some adverse impacts, but sufficient incentives would be offered to offset the impacts and even make participation financially attractive. Nevertheless, it is important to identify possible impacts so that landowners can consider them when making their decision to participate. Participant impacts could include the following:

1) Cost to purchase amendments to use with surplus surface waters. These would include amendments to improve infiltration and commercial fertilizers to replace the higher nitrogen levels of local groundwater. These would be needed due to the differences in surface and ground water quality.

2) Costs to construct new facilities (i.e. connection to the District's distribution system, larger well pump) needed to participate in the program.

3) Loss of surface water supply in a drought. The participant will agree to relinquish their surface water rights in a drought year. However, this would be accompanied by an increase in groundwater storage to help meet their demands. In addition, the Drought Plan includes a safety net allowing them to default on their agreement either due to extenuating circumstances or by paying a fee.

The impacts will differ for each landowner based on their facilities, water needs, historic water uses, and other factors. The proposed incentives may not make the Drought Plan attractive for all growers, but OCID expects that they will be sufficient for most growers.

Waterlogging

A potential impact could be higher groundwater levels that rise to the point of adversely impacting crops. OCID plans to restrict banking so that groundwater levels do not rise higher than 20 feet below ground surface. In fact, waterlogging does not occur until groundwater levels are less than 10 feet from the surface, but 20 feet was selected so there is a comfortable buffer zone. The District has an existing groundwater level monitoring program, and they recently installed six shallow wells to monitor groundwater levels for the pilot program.

PUBLIC PARTICIPATION

The Drought Plan was developed with input from a Groundwater Advisory Committee (GAC) comprised of District growers and several members of the District's Board of Directors. The GAC played a vital role in the development of the Drought Plan. In the future, the GAC will also assist District staff in overseeing the Drought Plan operations and monitoring.

A public outreach program was also implemented to educate landowners and solicit their comments on the Drought Plan. The public outreach program was not included in the original scope for developing the Drought Plan. Rather, the public outreach program was recommended by a GAC member, who, being a grower, recognized the importance and value of educating landowners on the intricacies and benefits of the program. Three meetings were held with local growers to discuss the project. Several handouts were given to all attendees including: list of Frequently Asked Questions (FAQs), informational brochure, participant worksheet (see Figure 2), and a PowerPoint Presentation summarizing all aspects of the Drought Plan. Results from the outreach program were generally positive, and OCID will probably perform more public outreach to garner further input and support.

CONCLUSIONS AND RECOMMENDATIONS

An in-lieu groundwater-banking program can offer the Orange Cove Irrigation District increased protection from droughts by increasing groundwater storage for use in dry periods. The details of the program will be evaluated and refined during a pilot program. Simulation of the Drought Plan shows that it could provide up to 15,000 AF of water in dry years. However, this quantity of water could not be banked in the local aquifer without causing potential waterlogging problems. The District will only be able to bank up to 9,000 AF of water, which is short of their goal of 15,000 AF of drought protection. While the in-lieu groundwater banking program cannot provide all of the District's needed drought protection, it is the most promising alternative from the standpoint of economics and being under local control. OCID plans to also implement other drought protection alternatives in combination with in-lieu groundwater banking to provide diversified and comprehensive drought protection.

REFERENCES

Friant Unit Contractors, *Water Needs Analysis*, March 7, 1988.

Orange Cove Irrigation District, Hills Valley Irrigation District and Tri-Valley Water District, *Orange Cove Groundwater Management Plan*, October 27, 1997.

Orange Cove Irrigation District, *Water Conservation Plan*, January 1998.

Provost and Pritchard Engineering Group, Inc., *AB303 Application for the Groundwater Monitoring and Drought Preparedness Program for Orange Cove Irrigation District*, January 2004.

Orange Cove Irrigation District and Provost and Pritchard Engineering Group, Inc., *Groundwater Monitoring and Drought Preparedness Program,* July 2006.

United States Department of the Interior Bureau of Reclamation Region II, *Geologic Study of the Orange Cove Irrigation District*, August 1947.

United States Department of the Interior Bureau of Reclamation Region II, *Water Supply Study of the Orange Cove Irrigation District, Fresno and Tulare Counties, California,* September 1947.

DEVELOPMENT OF AGRICULTURAL DROUGHT EVALUATION SYSTEM IN KOREA

Ki-Wook Park[1]
Jin-Taek Kim[2]
Uk-Jong Ju[3]

ABSTRACT

There are two ways to mitigate drought, structural and nonstructural measures. Structural measures include storage of irrigation water and development of emergency wells, nonstructural measures involve water saving management by early warning system.

To predict and evaluate drought for agriculture, we need to develop drought indices. Presently, drought preparedness are be classified by precipitation, reservoir storage, soil moisture in paddy and upland, and the growing status of crops. However, the indices lack clear quantitative criteria for consistent judgment. Consequently, improvements are needed in selection and utilization of proper drought indices to warn of oncoming drought.

The objectives of this study were to develop an Agricultural Drought Evaluation System, and to evaluate indices for current agricultural status using the system.

We considered several existing drought indices for application to Korea: Reservoir Storage Index (RSI), Standardized Precipitation Index (SPI), Mean Rainfall Index (MRI), Dry Day Index (DDI), Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), Percent of Normal, Deciles, and Percent of Median. We determined that four indices are applicable to Korea RSI, SPI, MRI and DDI.

The Agricultural Drought Evaluation System was developed using these four indices to analyze temporal drought status.

INTRODUCTION AND BACKGRUND

Drought is a normal feature of any climate. It is a temporary, recurring natural disaster that, originates from the lack of precipitation and brings significant economic losses. It is impossible to avoid drought, but we can develop drought preparedness and manage drought impacts. The success of both depends on how well we define and quantify drought characteristics.

In any region, drought is multi faceted and always derives from lack of precipitation, but drought may be affected by soil moisture, streams, groundwater, ecosystem functions, and human. This leads us to identify different types of drought. Operational definitions of drought vary, and are crucial for identifying the beginning and, end, degree of drought. The three main types of

[1] Researcher-Water Resources Division; Rural Research Institute; Korea Rural Community and Agricultural Corporation(KRC); 1031-7, Sa-Dong, Ansan-Si, Gyounggi-Do, Rep. of Korea, 426-170; pku@ekr.or.kr
[2] Senior Researcher-Water Resources Division; Rural Research Institute; Korea Rural Community and Agricultural Corporation(KRC); 1031-7, Sa-Dong, Ansan-Si, Gyounggi-Do, Rep. of Korea, 426-170; jtkim@ekr.or.kr
[3] Researcher-Water Resources Division; Rural Research Institute; Korea Rural Community and Agricultural Corporation(KRC); 1031-7, Sa-Dong, Ansan-Si, Gyounggi-Do, Rep. of Korea, 426-170; juj11@ekr.or.kr

drought are: meteorological, agricultural, and hydrological. Some researchers, particularly economists, also define drought in socioeconomic terms, measuring its impact on social and economic systems.

Many indices exist for analyzing drought status, for example: RSI, SPI, MRI, DDI, PDSI, CMI, and Percent of normal, Deciles, and percent of median. These indices use precipitation, stream flow, and surface water application to quantitatively evaluate drought.

There are two ways to mitigate drought. One is structural, and includes measures such as storage of irrigation water, development of emergency wells, and others. The other is nonstructural, including water saving management by the early warning system. To predict and evaluate agricultural drought, we need to develop improved nonstructural drought indices. Presently, we classify drought preparedness levels by considering precipitation, reservoir storage, soil moisture in paddy and upland, and the growing status of crops, but current qualitative indices lack rigor for consistent judgment. Clearly, we have not selected and utilized proper drought indices to provide early warning of drought outbreaks.

The objectives of this study are to develop an Agricultural Drought Evaluation System, and to evaluate indices for predicting agricultural drought status using the system

CURRENT STATUS OF AGRICULTURAL DROUGHT OCCURRENCE

Historical Drought Analysis

Drought reports published by the Korean government focus on extremely severe drought years, such as 1967-1968, 1994-1995, and 2001, during which the government conducted drought mitigation. But, most agricultural droughts are short temporally short (i.e., monthly, seasonal), and regional. Thus, we performed a newspaper database search for additional drought information for a representative historical period. We compiled climate data from 1966 to 2002 for the agricultural drought analysis. We retrieved 3,386 newspaper articles, of which 546 were agricultural articles. Monthly analysis of all articles yielded a good correlation with known severe drought periods: May 1967 (34 articles), July 1994 (40 articles), and June 2001 (26 articles). Most recorded droughts occurred during the Korean transplanting season, from May to June. The monthly and seasonal drought events we derived from this search are shown in Figures 1., and 2.

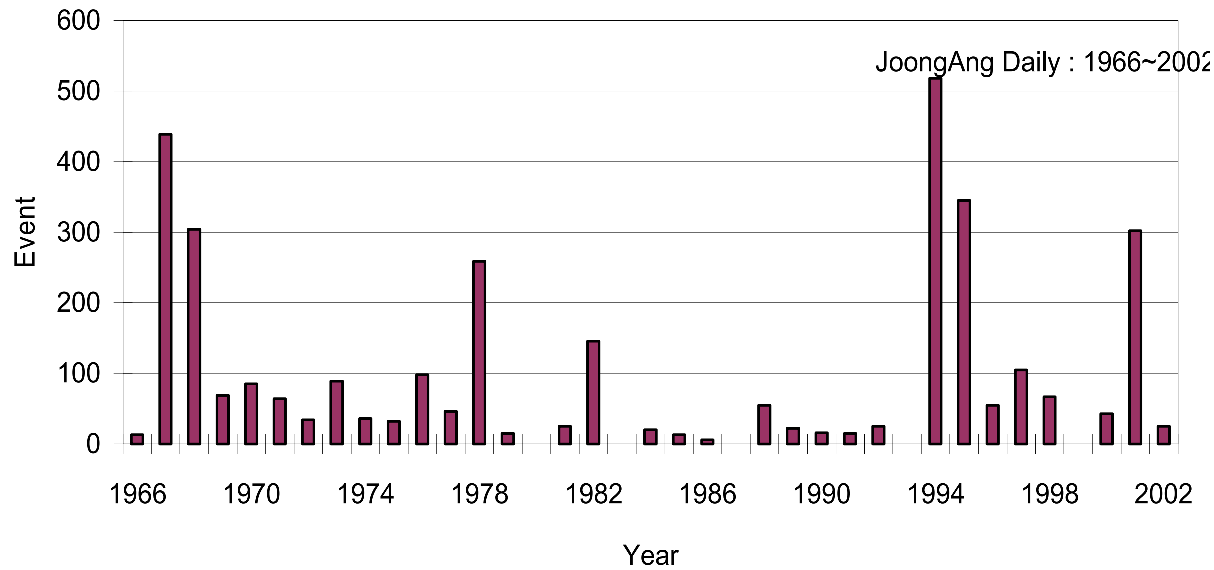
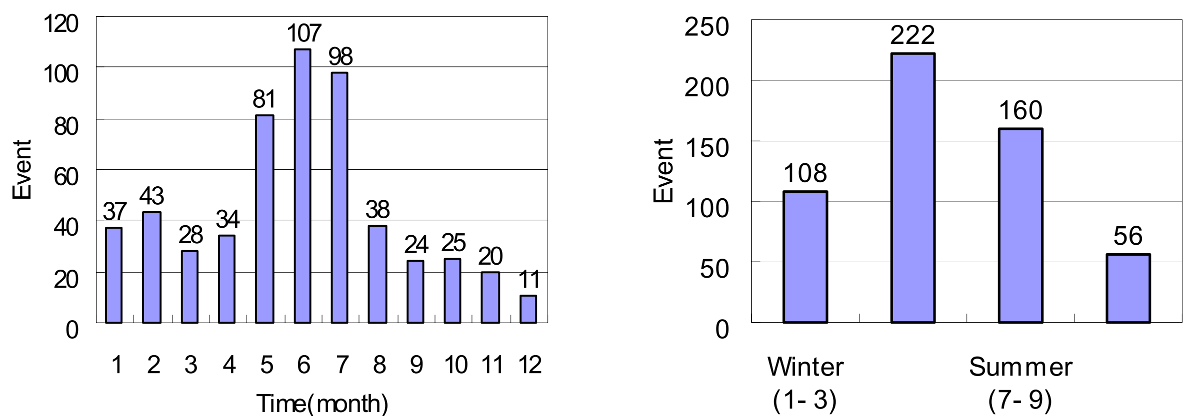


Figure 1. Drought events from the JoongAng Daily (1966-2002)



(a) Monthly (b) Seasonal

Figure 2. Temporal drought events

Quantifying Agricultural Drought

We used weighing factor analysis to quantify the relative severity of agricultural droughts. Table 1 shows the agricultural drought weighing factors. We recognized that recorded drought events were not limited to the agricultural sector only; therefore, we expanded our analysis to include economic and environmental factors. Soil moisture, stream flow, ground water, and economic conditions complicated the analysis. Figure 3 shows the results of weighing factor analysis and the relative severity of monthly drought events over the historical period.

Table 1. Weighing factors for agricultural drought

Agricultural		Economic		Environmental	
Event	Value	Event	Value	Event	Value
Delay of transplanting	10	Refugee	10	Drinking water shortage	7
Wilting	10	Income decline	10	Power limit	7
Lack of storage	7	Dispute	8	Power generation	6
Water contamination	6	Yield decrease	7	Other industry	4
Crop damage	6	Short of provision	6	Grain price	4
Water supply	5	Alternation crop	5	Disease	4
Auxiliary water source	4	Drought mitigation	4	Forest fire	2
Lack of rainfall	4	Livestock damage	3	Other	1
Lower river flow	4	Relief from drought	2		

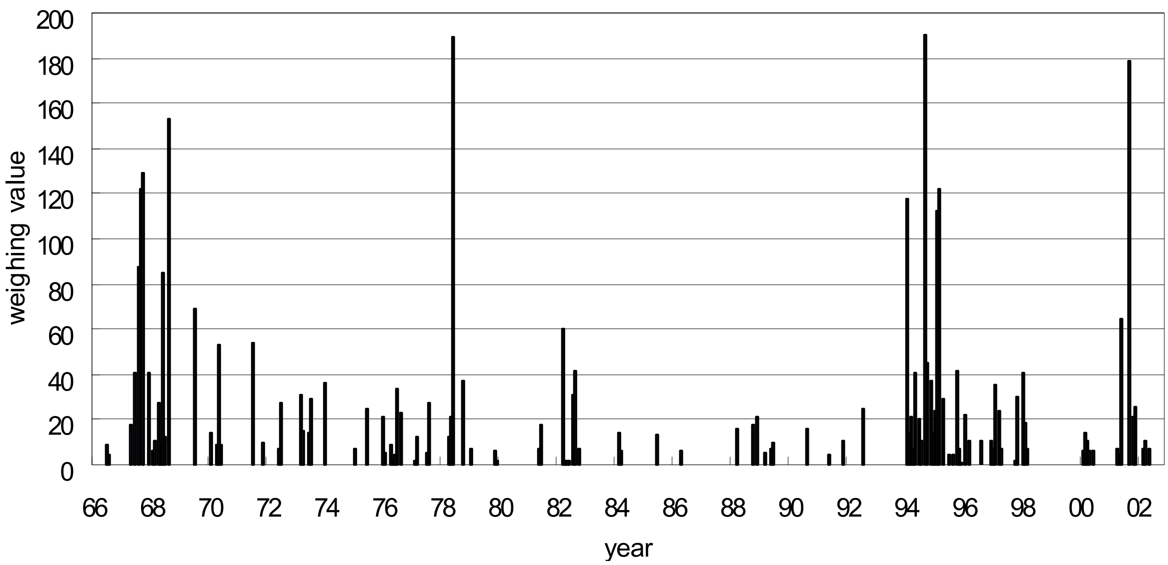


Figure 3. Weighing value of monthly drought events

DEVELOPMENT OF AN AGRICULTURAL DROUGHT INDEX

To develop an improved agricultural drought index, first we accessed the two fundamental available climate data sources—meteorological and daily reservoir storage data. Then, we determined the best existing indices for Korea and defined a useful system of drought stages. During agricultural drought analysis, we mapped drought status over time according to the drought stage classification we developed. As a check, we compared the frequency distributions of reservoir storage data and our derived drought stages.

Meteorological Data

Regional meteorological boundary are defined by local offices of the Korea Rural Community and Agricultural Corporation (KRC). We selected 76 meteorological stations for rainfall data analysis. These stations provide rainfall data for a minimum 30-year period. Each KRC local office compiles meteorological data from one or more stations.

Daily Reservoir Storage Data

Daily irrigation reservoir storage data were obtained from the Rural Water Information System (RWIS). RWIS has daily storage data for 3,277 reservoirs. These data are available for water and irrigation water users to determine effective water applications for paddy irrigation. The daily reservoir storage data are used for agricultural drought analysis.

Applicable Drought Indices for Korea

We considered the following existing drought indices as potentially applicable to Korea: RSI, SPI, MRI, DDI, PDSI, CMI, percent of normal, deciles, and percent of median. We determined that four indices are applicable to Korea: RSI, SPI, MRI, and DDI.

McKee et al.(1993) developed the Standardized Precipitation Index (SPI) for the purpose of defining and monitoring drought. SPI is based just on precipitation and requires less input data and calculation effort than other drought index. A Long-term precipitation record at the desired station is fitted to a probability distribution, which then transformed into a normal distribution. SPI may be computed with different time step (e.g., 1 month, 3 months, …, and 48months). Kim et al. (1999) introduced SPI application in Korea and 3-months delayed SPI is best results for agricultural drought analysis in Korea.

Monthly mean rainfall can directly displayed the water deficit during growing season. Watching the monthly rainfall data provides simple way to analysis the drought status. This value does not major factor for drought analysis. Mean Rainfall Index is helpful to decide the start of drought event.

Since the effects of drought often accumulate slowly over a considerable period of time and may linger for years after the termination of the event, the beginning and end of drought is difficult to determine. Because of this, drought is often referred to as a creeping phenomenon. Drought is caused by insufficient water supply from natural or artificial water resources. As a natural result, rainfall is irregular water source from atmospheric phenomena. Dry day continue for a long time, the water cannot provide sufficiently. The drought will be occurred as any time or any region. Numbers of dry day can help to determine when drought is beginning.

Drought Stage

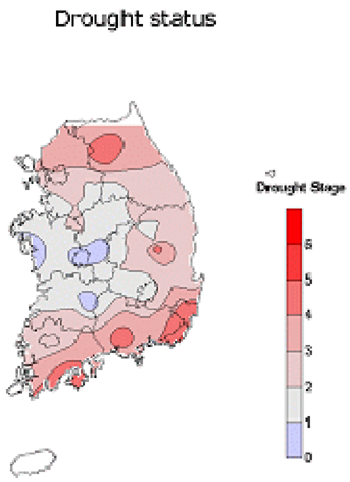
Droughts are identified as undergoing two or more stages, depending on the drought management agency. (The two main agencies for drought mitigation in Korea are the governmental Ministry of Agriculture and Forestry (MAF) and the Korea Rural Community and Agricultural Corporation (KRC).) MAF assigns two stages: the preparation stage and the mitigation stage. KRC uses four stages to describe the effect of droughts on irrigation reservoir storage: the ordinary/finishing, preparation, warning, and emergency drought stages.
We propose six agricultural drought stages (DS1-DS6). We classify each of our six drought stages by quantitative measures of the four applicable drought indices mentioned earlier: RSI, SPI, MRI, and DDI. Table 2 shows the agricultural drought stages and recommended guidelines for agricultural drought evaluation.

Table 2. Drought stages for agricultural drought

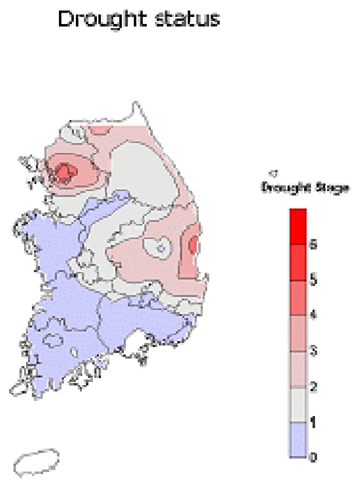
Guideline			Drought stage	RSI (%)	SPI	MRI (%)	DDI (days)
MAF*		KRC**					
Preparation stage	Ordinary	Ordinary/Finishing stage	DS1	70	< -1.0	85	10
			DS2	70	< -1.5	75	15
Mitigation stage	Worrying	Preparation stage	DS3	50	< -2.0	60	21
		Warning stage	DS4	50	< -2.0	50	21
	Spreading	Emergency stage	DS5	30	≤ -2.5	40	30
			DS6	30	≤ -2.5	40	30

* MAF; Ministry of Agriculture and Forestry, Korea

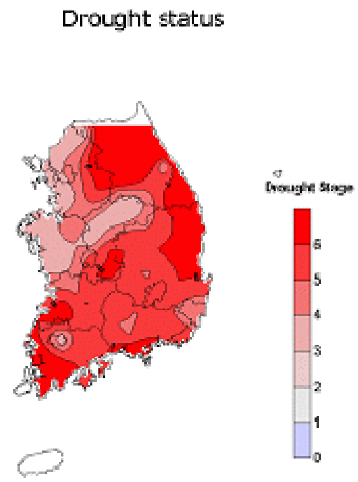
** KRC; Korea Rural Community and Agricultural Corporation



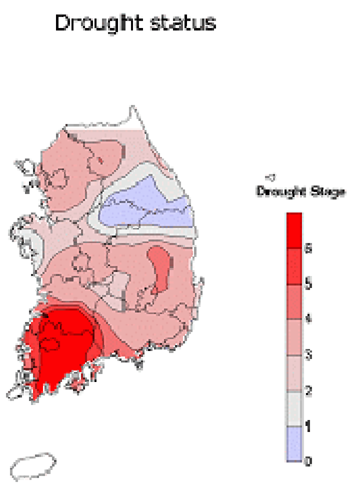
(a) 1993.9



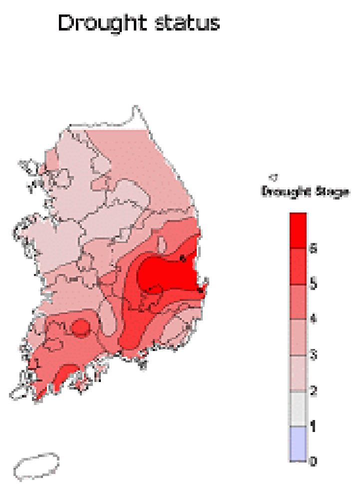
(b) 1993.12



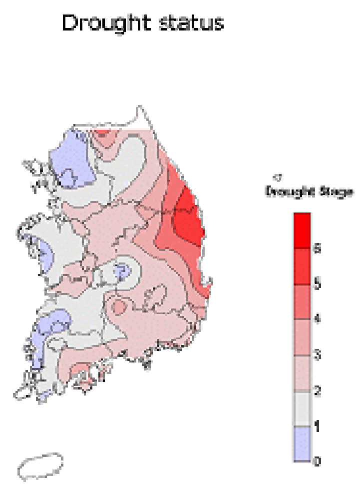
(c) 1994.3



(d) 1994.6



(e) 1994.9



(f) 1994.12

Figure 4. Agricultural drought analysis (1994)

Comparison of Results

We compared the frequency distributions of reservoir storage data and derived drought stages. The results showed in Table 3. Countrywide drought occurs during 2001. Reservoir storage reduced from May, 2001. But, drought phenomenon is showed early spring. In actually, new method showed 2~3 month before than reservoir storage. This implies the new method can express for drought phenomenon and suitable for drought mitigation.

Table 3. Comparison of results between reservoir storage data and derived drought stage for 2001

Classification		Month											
		J	F	M	A	M	J	J	O	S	O	N	D
		Number of local KRC offices											
Reservoir storage	Over 70%	86	86	91	91	75	12	64	68	16	16	22	26
	50-70%	0	5	0	0	16	41	23	22	47	35	39	43
	30-50%	5	0	0	0	0	31	4	1	24	34	25	22
	Below 30%	3	3	3	3	3	10	4	4	7	9	8	3
Drought stage	0-1.0	55	83	0	0	0	46	42	5	4	31	0	41
	1.0-2.0	29	8	8	0	0	17	32	16	1	23	0	19
	2.0-3.0	6	1	8	0	0	17	12	14	4	13	2	12
	3.0-4.0	2	2	56	7	0	6	6	17	13	10	4	7
	4.0-5.0	1	0	17	20	2	1	2	26	11	5	5	7
	5.0-6.0	1	0	5	67	92	7	0	16	61	12	83	8

DEVELOPMENT OF AGRICULTURAL DROUGHT EVELUATION SYSTEM

Agricultural drought evaluation and information system are developed in order to effective drought management in Korea. Drought evaluation system is composed two main modules: the computation module, the operation module. Computation module is calculated the drought index according to weather data and storage data. These results stored in database and used for drought evaluation. These all program operated on prompt mode of DOS environment because this module coded ANSI-C language. The drought evaluation system operated in IBM-PC.

ADIS, Agricultural Drought Information System, is developed in order to provide drought information to water manager. They are used this data to decide irrigation water supply and to make drought mitigation of KRC local office level.

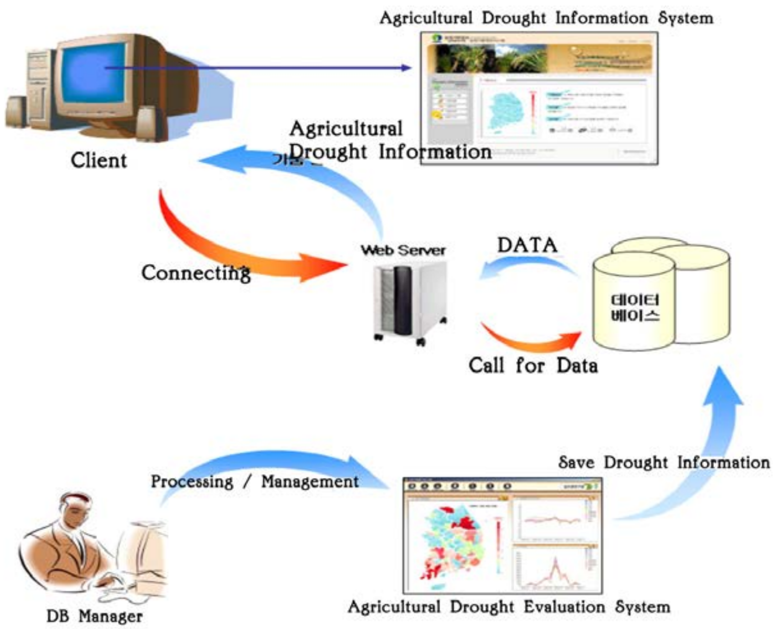


Figure 5. Conceptual diagram for agricultural drought evaluation system

SUMMARY

We are making good progress in developing an Agricultural Drought Evaluation System for Korea. We have classified recent historical agricultural drought by type of event and time, and quantified drought history by weighing value analysis. We initiated the development of an agricultural drought index for Korea, considering available climate data, suitable indices, and drought stage classification. We proposed six agricultural drought stages for drought evaluation and mitigation, and applied the classification spatially to map past agricultural drought. Our drought stage classification showed improvement over using reservoir storage data alone. Currently, we are proceeding with development of the agricultural drought evaluation system, which we will use to evaluate drought indices for assessing current agricultural status.

REFERENCES

Bae, Seung Jong, Ha Woo Chung, and Jin Yong Choi, 1999. Agricultural Drought Analysis using Soil Water Balance Model and Geographic Information System. J. of KASE 41(6): 33-43.

Guttman, N.B. 1998. Comparing the Palmer drought index and the standardized precipitation index. Journal of the American Water Resources Association 34(1): 113-121.

Hayes, M. J. 2003. What is Drought? (http://drought.unl.edu/whatis/indices.htm)

Jensen, M.E., R. D. Burman and R. G. Allen. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practices No. 70. New York, NY.

Kim, Sang Min and Seung Woo Park. 1999. Calculation and comparison of drought indices on major weather station in Korea. J. of KSAE 41(5) 43-52.

Palmer, W. C. 1968. Keeping track of crop moisture conditions, Nationwide : The new crop moisture index. Weatherwise 21: 156-161.

RESTORATION IN THE ECO-CONSERVATION AREA OF THE GENTE RIVER OF *PUNGITIUS SINENSIS*

Hirose Shinichi[1]
Takimoto Hiroshi[2]

ABSTRACT

The Gente River, 3km in length and with a 5.1 m-wide bottom, is a drainage canal for the farming area. All its weeds-rampant soil riverbed was renovated in an eco-friendly design between 1996-2001. But the renovation made the flow velocity of the canal a little too high for the propagation of Tomiyo, a tiny fish species (*Pungitius Sinensis)*. To provide Tomiyo with a comfortable niche to propagate in, an eco-conservation area was created halfway down the renovated canal in 2000. The area is a 100 m-long and 3.3 m-wide gravel-bottomed stream laterally added to the main stream. This study was aimed at tracking how Tomiyo fared in this new environment.

The capture survey of Tomiyo was conducted in the quadrat section of the eco-conservation area four times over a period of time 5 to 11 months after the completion of the area. The results revealed that the population density of Tomiyo under the waterweeds ranged from 1.19 to 3.52 fish/m. The marking survey was conducted six times over a period of time 18 to 47 months after the construction of the area. The results revealed that the population density of Tomiyo under the waterweeds ranged from 2.61 to 5.92 fish/m^2. Another capture survey (control) had been conducted at five sections of the Gente River before its renovation. The result had revealed that the density of Tomiyo under the waterweeds ranged from 1.93 to 2.44 fish/m^2. The above surveys of the density of Tomiyo differed from each other in the time spent, in the capture techniques and in the calculation methods. But they at least confirmed the following two facts:

1) In the quadrat section, Tomiyo living under the waterweeds whose coverage rates were still less than 50% showed levels of density similar to the ones in the pre-renovation stream.
2) In the eco-conservation area as a whole, Tomiyo living under the waterweeds whose coverage rates were around 70% showed levels of density far exceeding the ones in the pre-renovation stream.

From these results we might conclude that the eco-conservation area serves well to preserve a good enough environment for Tomiyo to propagate in.

Keywords : Tomiyo, eco-friendly canal design, eco-conservation area, endangered species, Jolly-Seber method, population density of the species

---

[1]Professor, Dr., Department of Environment System Engineering, College of Technology, Toyama Prefectural University, Imizu, Toyama, 939-0398 Japan , Tel: 0766-56-2495, Fax: 0766-56-6084 E-mail: hirose@pu-toyama.ac.jp
[2]Assistant Professor, Dr., Ditto. E-mail: takimoto@pu-toyama.ac.jp

INTRODUCTION

The Gente River is a 3km-long canal flowing north down the northernmost part of the Shogawa alluvial fan in Toyama prefecture, Japan and it is used as a drainage canal for paddies (Figure 1, Table 1). The stream is fairly clean thanks to an abundant supply of effluent seepage and abounds in aquatic animal and plant species such as *pungitius sinensis*, locally called Tomiyo and *sparganium japonicum*, locally called Nagaemikuri (Photo 1). The former is already listed as an endangered species in the local red data book (Depertment of life environment of Toyama prefecture 2002) .

Figure 1. Location of the Gente River

Table 1. Design specifications of the Gente River

Length	3028.5 m	Bottom width	4.1~5.1 m
Bottom slope	1/500	Design velocity	1.45~1.92 m/s
Revetment height	1.0~1.2 m	Design capacity	6.04~18.25 m^3/s

On the other hand, the Gente River was overrun by waterweeds, incurring both a reduction in drainage performance of the canal and an extra burden on the users in terms of maintenance and operation.

Pungitius pungitius sinensis

Tomiyo

Sparganium japonicum

Nagaemikuri

Photo 1. Tomiyo and Nagaemikuri of the Gente River. Thanks to an abundant supply of effluent seepage, the stream provides a comfortable habitat for 17 species of fish and 17 species of waterweeds. An adult Tomiyo is about 6 cm in length.

In Japan amid the general public's enhanced awareness of the natural environment, there has been a growing interest in going back to a quasi-natural canal construction technology. The Gente River was rehabilitated using an eco-friendly canal design in a water environmental improvement project implemented between 1996 and 2001 by the local government. Specifically, its bottom was alternately lined with flat blocks and cobble-filled frame blocks, which means that an average of 80% of the bottom was covered with concrete and the rest with cobbles. This construction design was adopted for the dual benefit of facilitating waterweeds control and of minimizing damage to aquatic life.

Several years after the remodeling of the canal bed, waterweeds and Tomiyo came back. This suggests that a good canal environment for Tomiyo's survival was revived. But a series of water balance surveys conducted a hundred times in this remodeled canal has revealed that the flow velocity ranges flow 0.15 ~ 0.99 cm/s. This level of flow velocity is not much of a problem for Tomiyo's survival, but hinders their comfortable propagation.

To make it easier for Tomiyo to propagate, a 100 m-long eco-conservation area was created halfway down the canal in 2000. This study was aimed at tracking how Tomiyo fared in this new environment.

ECO-CONSERVATION AREA OF THE GENTE RIVER

The specification of the eco-conservation area

The population density of Tomiyo tends to fall when the flow velocity exceeds 0.50m/s (Hokuriku Bureau of Ministry of Agriculture 1999). After the renovation of the riverbed, the Gente River showed a level of flow velocity a little too high for the propagation of Tomiyo. That was why a 100 m- long eco-conservation area was created halfway down the Gente River. The area was a 3.3 m-wide gravel-bottomed stream laterally added to the Gente River proper.

To facilitate our survey, we provided a quadrat section in the middle of the eco-conservation area. This section consisted of ten unit quadrats, ranging from St.10 down to St.1. A unit quadrat was 2.7 m-long and 3.3 m-wide (Figure 2).

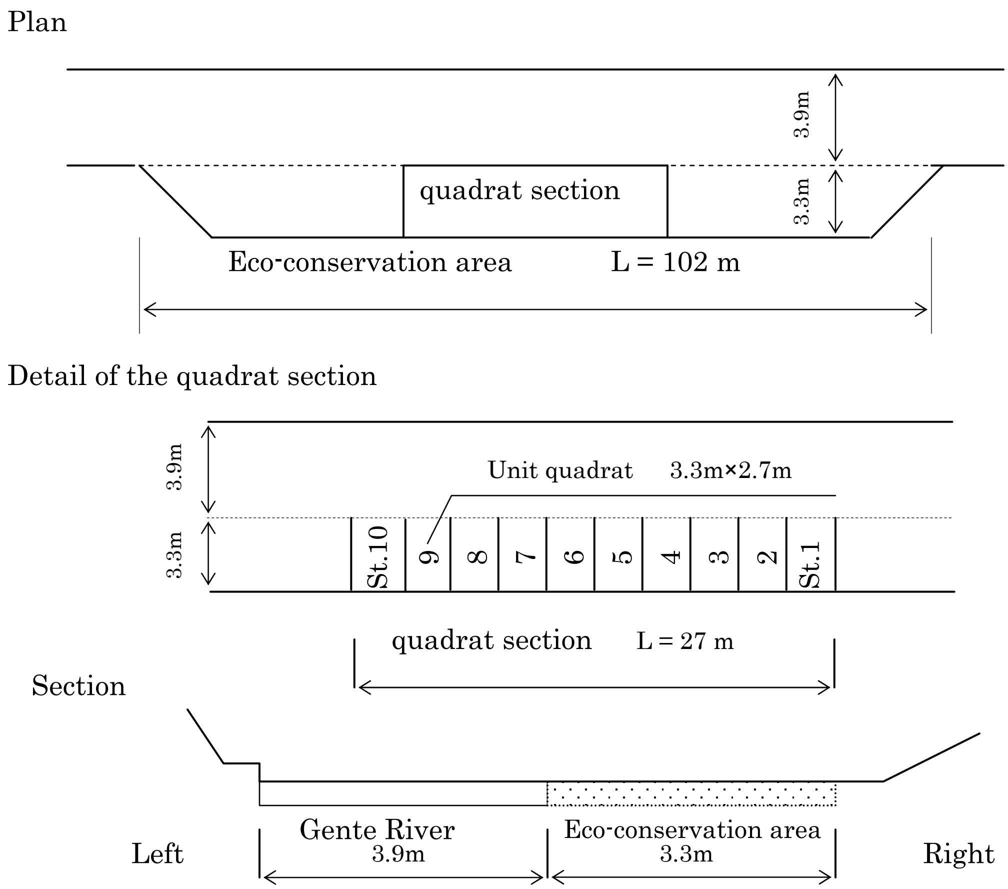


Figure 2. Specification of the eco-conservation area

<u>The flow condition of the eco-conservation area</u>

The flow condition was observed for three consecutive days at St.10 and St.1 at the same time as the marking survey of Tomiyo. The averaged data are shown in Table 2.

For the measurement of flow velocity (V), we used a propeller electric tachometer manufactured by Tohodentan Inc. To examine bucket-sampled water for the temperature (T), pH, electric conductivity (EC), dissolved oxygen (DO), we used a handy water quality analyzer manufactured by Horibin Ta Inc. As for flow velocity (V) and water depth (H), we surveyed the main stream too by way of providing the control. The averaged flow velocity of the eco-conservation area was 0.35 m/s and lower than that of the main stream, and the flow temperature was higher than 6˚C even in February under the influence of effluent seepage. The Ministry of the Environment stipulates as an index of clean water the environmental criterion of

Class AA representing the pH value of 6.5 ~ 8.5 and the DO value of 7.5 mg/ℓ or over. Three years after its construction, a survey of the eco-conservation area provided relevant data satisfying this criterion. From all this the eco-conservation area might be judged as a comfortable niche for Tomiyo to propagate in.

Table 2. Flow condition of the eco-conservation area

Date	V (m/s)		H (m)		T	pH	EC	DO	So
	L	R	L	R	℃		ms/cm	mg/ℓ	%
Sept 2001	0.48	0.32	0.27	0.27	18.5	7.49	0.158	7.20	78
Feb. 2002	0.43	0.34	0.53	0.52	6.9	6.98	0.180	6.45	60
Sept 2002	0.53	0.46	0.36	0.35	18.1	7.72	0.210	6.32	69
Feb. 2003	0.34	0.07	0.49	0.49	7.9	7.65	0.141	16.15	139
Sept 2003	0.60	0.54	0.38	0.37	17.0	6.46	0.139	10.26	110
Feb. 2004	0.49	0.40	0.50	0.50	8.1	6.68	0.151	11.01	117
Avarage	0.48	0.35	0.42	0.42	12.7	7.16	0.163	9.57	96

L : Eco-friendly design, R : Eco-conservation area
So : Saturated Oxygen

Restoration of the waterweeds

In order to confirm the restoration of the waterweeds in the eco-conservation area, seven surveys were conducted in the quadrat section on the coverage rates of waterweeds i.e. what percentage of the bottom space was covered with the waterweeds. These surveys were executed by means of photo analysis between August 2000 (five months after the construction of the eco-conservation area) and July 2002, 2 years and 4 months after.

The growth curve obtained at the end of the surveys for all the waterweed species occurring in the quadrat section indicated that with a coverage rate of 78.1% the community climax had been reached with Nagaemikuri as a predominant species. Another survey for the Gente River proper, revealed that 5 years after the eco-friendly renovation the climax had been reached with a coverage rate of 65.6%. These results mean that the waterweeds in the eco-conservation area were restored twice as fast as those in the renovated canal.

RESTORATION OF TOMIYO

Capture survey in the quadrat section

(1) Survey Method. The capture survey was conducted four times in the quadrat section over a period of time 5 to 11 months after the construction of the eco-conservation area.

① Capturing of Tomiyo in the unit quadrat

a. Tomiyo were caught with a triangle net, 1.5 m wide, 1.2 m high and 0.5 m long , which is used for fishing small fry.
b. Tomiyo live usually under the waterweeds. The riverbed of the downside boundary of the unit quadrat was mowed one day in advanced so that the base of the net would snugly touch

the riverbed.

c. Three chasers drove Tomiyo out of the waterweeds into the net from the upside boundary of the unit quadrat.

d. Then we counted the number of Tomiyo captured.

② The density of Tomiyo under the waterweeds in the quadrat section : D (fish/㎡) was calculated from the number of Tomiyo caught in the unit quadrat : N (fish) and the area of the waterweeds in the unit quadrat : A (㎡)

$$D = N / A \qquad (1)$$

<u>(2) Results and discussion</u>

The average of the densities obtained from ten unit quadrats of the section is shown in Figure 3 together with their standard deviations, the averaged flow velocities and the averaged waterweed coverage rates. The four surveys we conducted showed that the coverage rates of the waterweeds ranged from 29 to 50%, the flow velocities from 0.22 to 0.49 m/s and the densities of Tomiyo under the waterweeds from 1.19±0.87 to 3.52±2.26 fish/m^2.

Only eleven months after the construction of the area, when the coverage rates of the waterweeds were still lower than 50%, the flow velocities were already lower than 0.50 m/s, providing a comfortable condition for Tomiyo to propagate in.

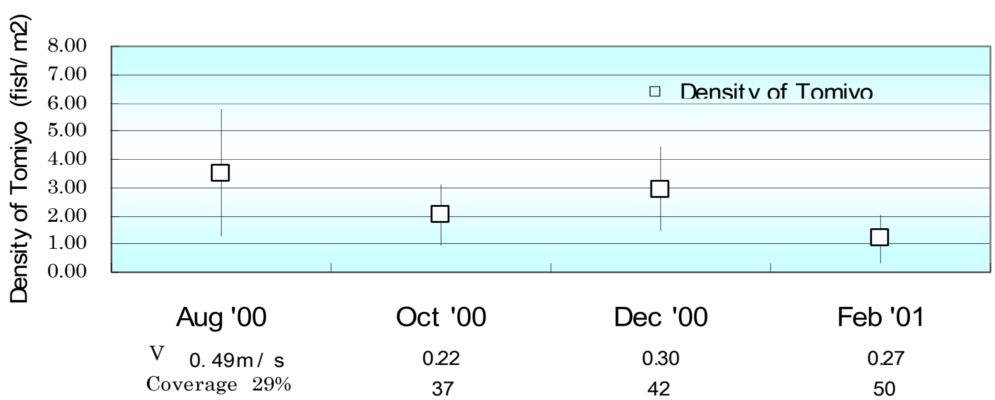


Figure 3. Density of Tomiyo under the waterweeds in the quadrat section. The quadrats section was completed in March 2000. A vertical line represents a standard deviation.

<u>Marking survey in the quadrat section</u>

One year and a half after the construction of the eco-conservation area, when Nagaemikuri was gradually restored to the status of predominant species and the coverage rate of the waterweeds was higher than 70%, we attempted to estimate statistically the number of Tomiyo living in the eco-conservation area by using a fully stochastic model derived by Jolly-Seber.

This stochastic model allowing for birth, death, immigration and/or emigration was designed to fit the majority of capture-recapture problems involving a single open population. The word single here denotes a population covering an area within and/or across whose borders the animals (e.g. Tomiyo) are free to move and to mix with others of their kind, but which is regarded as a single area in respect of which the population parameters are to be estimated. In this model by Jolly-Seber at least three capturing operations and two marking and release operations are required.

The life span of Tomiyo in the Gente River is approximately one year, and they spawn in spring and then die(Hokuriku Bureau of Ministry of Agriculture 1999). The marking survey was executed twice a year, in February (for parents) and September (for children). These surveys were repeated for three consecutive years. The coverage rates of weeds were visually estimated by three evaluators.

(1) The Concept of Jolly-Seber's Three-point Marking Survey (Jolly,G.M.1965) A marking survey is a way of finding the size of the population of fish from the total of the fish marked and the ratio of the marked fish in the sample fish captured. Suppose you capture n_1 fish out of a population and mark and release them. Suppose that, when these n_1 fish are just about well mixed with the rest of the original population, you capture n_2 fish and find m_2 fish out of these n_2 to have been marked. Let us assume the size of the above mixture to be N_2 (an unknown quantity) and, let us assume the number of marked fish in this N_2 to be M_2. Then we obtain a proportional relationship: $M_2/N_2 = m_2/n_2$.

In Jolly-Seber's three-point method, the size of the target population of fish is estimated from three samplings on three consecutive days. Here, i = 1 ~ 3 is the ordinal number. On the first day (i = 1) and on the second day (i = 2), marking, counting and releasing are executed. On the third day (i = 3), only counting is executed. Based on these counting results, the size of the population of the fish on the second day (i = 2) are estimated.

(2) The survey procedure

① The first day

a. Counting captured fish
b. Measuring the length of the fish
c. Marking the fish with a primary sign
d. Releasing the marked fish

② The second day

e. Counting captured unmarked and primary-sign marked fish separately
f. Measuring the length of the fish
g. Marking the fish with a secondary sign
h. Releasing the marked fish

③ The third day

i. Counting captured fish according as they are unmarked, marked with a primary-sign, marked with a secondary sign or doubly marked (with a primary and a secondary sign)
j. Measuring the length of the fish
k. Releasing the fish

<u>(3) Marking method</u> Fish were marked by injecting their left side with fluorescent coloring with a hypodermic. The fluorescent sign was 5 ㎜ long, long enough to detect. For the two kinds of signs different colorings were used. The fluorescent coloring used was visible elastomer manufactured by Northwest Marine Technology Inc.

<u>(4) Results and discussion</u> The data obtained are shown in Table 3. The estimated total number of Tomiyo with the standard deviation, the flow velocity and the coverage rates of the waterweeds are shown on Figure 4. The estimated density of Tomiyo under the waterweeds with the standard deviation, the flow velocity and the coverage rates of the weeds are shown in Figure 5. The six surveys revealed that the coverage rates of waterweeds were 60～80%, the flow velocity 0.07～0.54 m/s and the density of Tomiyo under the waterweeds 2.61±0.92～5.92±2.10 fish/㎡.

Table 3. Result of the Marking Survey

Month	Date (i=1,2,3)	Released fish	Marked fish $i=1$	Marked fish $i=2$	Marked fish $i=1,2$	Estimated Total Number of Tomiyo (N)	Coverage waterweeds (%)	Coverage waterweeds (m²)	Density of Tomiyo under the waterweeds (N/m²)
	i=1	287							
Sept 01	i=2	178	39			758± 182	70	235.62	3.22± 077
	i=3	177	20	25	3				
	i=1	262							
Feb 02	i=2	185	16			1394± 495	70	235.62	5.92± 2.10
	i=3	233	13	19	4				
	i=1	153							
Sept 02	i=2	149	23			1072± 318	80	269.28	3.98± 1.18
	i=3	133	22	23	0				
	i=1	121							
Feb 03	i=2	131	22			703± 246	80	269.28	2.61± 092
	i=3	117	11	11	4				
	i=1	119							
Sept 03	i=2	108	24			781± 269	80	269.28	2.90± 100
	i=3	108	18	10	3				
	i=1	89							
Feb 04	i=2	90	13			713± 364	60	201.96	3.53± 1.80
	i=3	38	7	7	0				

The space of the eco-conservation area is 336.6㎡

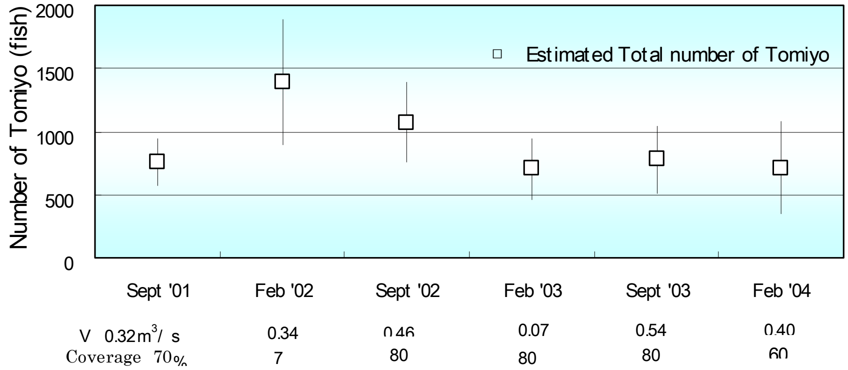


Figure 4. Estimated total number of Tomiyo at the eco-conservation area completed in March 2000. A vertical line represents a standard deviation.

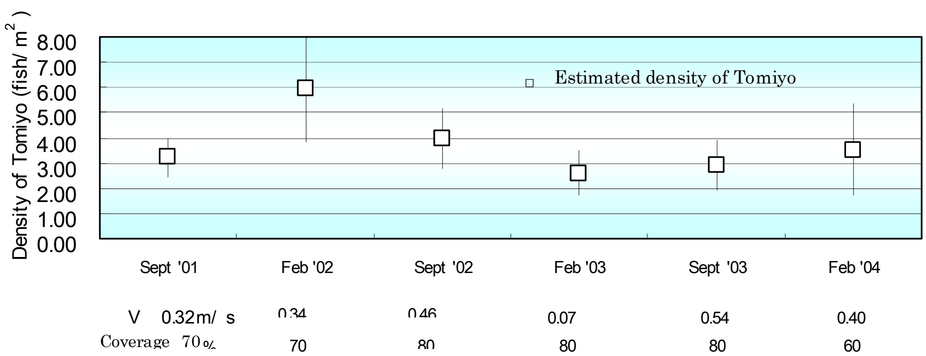


Figure 5. Estimated density of Tomiyo under the waterweeds at the eco-conservation area completed in March 2000. A vertical line represents a standard deviation.

Capture survey on the pre-renovation Gente River (Hokuriku Bureau of Ministry of Agriculture 1999) .

(1) Method of the survey   In September 1997 a capture survey was conducted on Tomiyo in the pre-renovation Gente River by the Hokuriku Bureau of Ministry of Agriculture and Forestry, ten times at random at sections A,B,C,D and E. The area of each section is approximately 1 ㎡.

(2) Results and discussion   Figure 6 shows the averaged density of Tomiyo with the standard deviation, the flow velocity and the coverage rates of the waterweeds. The ten survey revealed that the pre-renovation density of Tomiyo under the waterweeds was 1.93±1.49～2.44±1.12 fish/m^2.

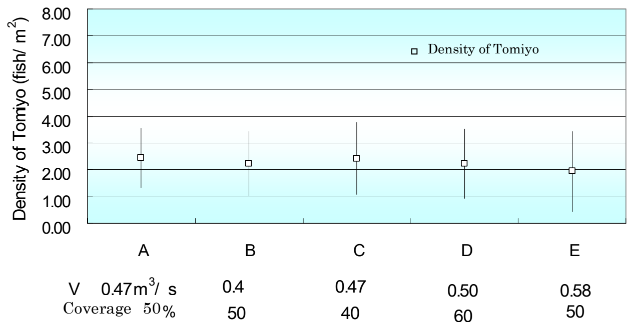


Figure 6. Pre-renovation density of Tomiyo under the waterweeds in the Gente River in September 1997.

DISCUSSION AND CONCLUSION

The Gente River was renovated using an eco-friendly canal design. But the flow velocity of the canal turned out to be a little too high for the propagation of Tomiyo. To provide Tomiyo with a comfortable niche to propagate in, an eco-conservation area was created halfway down the canal. Shortly after the construction of the eco-conservation area, the density of Tomiyo in the quadrat section was already revealed to be 1.2～3.5 fish/㎡ even though the coverage rate of the waterweeds was still less than 50%. This range of habitation densities was as high as the pre-renovation densities in the Gente River proper, 1.9～2.4 fish/㎡. Once the coverage rate of the waterweeds was over 70%, the densities of Tomiyo in the whole eco-conservation area estimated on the stochastic model was found to be 2.6～5.9 fish/㎡. These densities were higher than the pre-renovation densities of 1.9～2.4 fish/㎡ on Gente River. These three dada items were obtained by the three different survey methods in point of the capture effort, the capture technique and the calculation method. These data are not strictly comparable. However, since the pre-renovation density of Tomiyo was found to be restored, the eco- conservation area can be expected to contribute greatly to the preservation of the eco-system of the Gente River involving Tomiyo among others.

REFERENCES

Department of life environment of Toyama prefecture, 2002, The red data book in Toyama (in Japanese), p.87

Hokuriku Bureau of Ministry of Agriculture, Forestry and Fishery, 1999, Follow-up report on the change of the environment in the Gente River Project (in Japanese), p.82
ditto, p.75

ditto, pp.83～84

Jolly, G.M. 1965, Explicit estimates from capture-recapture data with both death and immigration-stochastic model, Biometrika, 52, pp.225～247

BEAN YIELD AND ROOT DEVELOPMENT IN DIFFERENT SOIL MANAGEMENTS UNDER A CENTER PIVOT SYSTEM

Leonardo Pretto de Azevedo[1]
João Carlos Cury Saad[2]
Marcelo Augusto de Aguiar e Silva[3]

ABSTRACT

The bean culture is part of crop rotation used by irrigators from the southwestern region of the state of São Paulo, who perform the no-tillage soil management as a form of sustainable soil use. The effect of this conservationist practice on soil compaction, root development and bean culture production components in relation to the conventional management was the objective of this work. The experiment was conducted at the Buriti-Mirim Farm, Angatuba, SP, Brazil, using an 18ha area irrigated through center pivot system divided into two types of soil managements: conventional management and no-tillage management. Crop production components, soil cone index and root development components (distribution in the soil profile, length, surface, diameter and dry matter) were evaluated. Although the no-tillage management had presented lower compaction at the most superficial layers and more uniform root distribution in the soil profile, the managements evaluated were not significantly different in relation to crop productivity.

INTRODUCTION AND BACKGROUND

Soil management

The different management systems affect soil density and porosity, directly influencing the root system development and crop productivity. The incorrect use of machines and agricultural accessories leads to increases on the soil density at the sub superficial layer and has been pointed as one of the main causes for deterioration of the soil structure and reductions on the crop productivity (Campos et al., 1995). According to Pedroso & Corsini (1983) and Silva et al. (1986), alterations on the soil structure due to conventional management practices also affect its drainage in function of the reduction on the volume of macropores, modifying the diffusion of water and gases and making the plant root development difficult. If intensive tillage is responsible for the soil deterioration, its reduction and the accumulation of organic residues at the soil surface could probably change this condition (Silveira Neto et al., 2006). The adoption of rational techniques for soil and water conservationist management is vital for sustainability so that these resources will be preserved along time with sufficient quantity and quality for the maintenance of satisfactory productivity levels (Wutke et al., 2000).

[1]Graduate, Agricultural Science School, São Paulo State University, Rua José Barbosa de Barros, 1780, Botucatu, SP, 18610-307, Brazil; pretto@fca.unesp.br
[2]Professor, Agricultural Science School, São Paulo State University, Rua José Barbosa de Barros, 1780, Botucatu, SP, 18610-307, Brazil; joaosaad@fca.unesp.br
[3]Graduate, Agricultural Science School, São Paulo State University, Rua José Barbosa de Barros, 1780, Botucatu, SP, 18610-307, Brazil; aguiaresilva@fca.unesp.br

In this context, the no-tillage technique has been recommended as alternative to avoid the undesirable effects of inadequate and repetitive soil preparation (Chan et al., 1992). It deals a management system where the sowing is performed on the remainders of the previous culture without drastic soil mobilization, in other words, without its preparation or mobilization before sowing (Stone and Silveira, 1999). Although this technique could increase the volume of water stored and available to plants, Klein and Libardi (1998) explain that the soil management under no-tillage system also increases the soil density and penetration resistance. According to Silveira Neto et al. (2006), this increase on the soil density at the most superficial layers has led some farmers from the Brazilian Cerrado vegetation to use plow or scarifier in areas so far conducted under no-tillage system, also acting in the nutrients redistribution in the soil profile. According to Silveira et al. (1998), such procedure does not affect the soil management conservationist aspect at all, once the no-tillage system is again employed in subsequent tillages. The use of no-tillage system and irrigation as conjugate techniques has shown to be promising considering the improvement of the soil exploitation and its maintenance. Stone & Moreira (2000; 2001) verified that the no-tillage system provided higher water economy when compared to other soil management systems; besides, this system would improve the soil physical characteristics along the years, once the increase on the organic matter content on the soil surface layer may reduce its density.

Root development

Since the no-tillage system improves the soil structure and water availability, a higher root development and hence a higher productivity are expected for this type of soil management; however, the effects of different soil management on root development and bean plant yield are not yet well determined. In general, root elongation is only possible when the root growth pressure is higher than the soil mechanical resistance to penetration (Passioura, 1991). According to Freddi et al. (2006), this resistance exerts great influence on the vegetal development, once the root growth and crop yield change is inversely proportional to their value. Mechanical resistance to penetration values ranging from 1000 to 3500kPa may generally restrict or even hinder the root development and growth. (Canarache, 1990; Merotto & Mundstock, 1999). According to Arshad et al. (1996), these values may range from 2000 to 4000kPa. More specifically for bean crop, Carvalho et al. (2006) concluded that soil mechanical resistance to penetration values ranging from 1290 to 2870 kPa are not restrictive to productivity. Richther et al. (1990) worked with different cultures and obtained higher root production using no-tillage system than in conventional management system; however, the highest amount of roots obtained with the no-tillage system was found at the first 15 cm of soil. Stone & Silveira (1999) studied the effect of different soil managements on productivity, water availability and root development of bean crops and verified that the no-tillage system presented higher productivity with higher water economy; however, the root system depth distribution was more uniform in plow-prepared soils. Stone (2002) worked with bean crop for four consecutive years using three soil preparation systems (no-tillage, plowing with plowing grid and moldboard plow) and observed that from 76 to 90% of roots were found at the first 30 cm deep in the soil.

Bean yield

In relation to bean yield, Knavel & Herron (1986), Mullins & Straw (1988), Sampaio et al. (1989) and Siqueira (1989) verified higher productivities in conventional management when compared to no-tillage system. In the study of Stone (2002), the no-tillage system presented lower number of pods per plant and lower mass of 100 grains and hence lower productivity in relation to the other soil management systems; however, the author attributed the lower bean yield to the lower N content in plants and concluded that the bean plant yield under no-tillage system increases with the adoption time of this system. Other important aspects are related to reductions on productivity in the no-tillage system. Arf et al. (2004) observed that soils prepared with moldboard plow and with plowing grid produced higher amount of grains in relation to the no-tillage system, once the dead coverage of this system provided higher humidity in the soil surface, thus favoring the attack of the "white mould". Mullins et al. (1980) and Zaffaroni et al. (1991), however, found no differences in the bean plant yield between no-tillage system and conventional management. According to Lopes et al. (2004), no significant differences in relation to water storage and grain productivity between no-tillage system and conventional management were found either.

Objectives

Due to the economic and environmental importance that the conventional management and the no-tillage systems represent for farmers from the southwestern region of the state of São Paulo, the objective of this work was to evaluate how these systems influence the compaction (soil cone index), root development and yield of beans irrigated through central pivot system.

MATERIAL AND METHODS

The experiment was conducted in an 18ha area irrigated through center pivot system at the Buriti-Mirim Farm, Angatuba, SP, Brazil during the second semester of 2003. The culture used was bean (*Phaseolus vulgaris* L.) cultivar Rubi, which sowing occurred at August 2 and the harvest at November 25, 2003, summing up 116 days of culture cycle. The experimental design was fully randomized with two treatments: the no-tillage and conventional managements with 13 parcels each. The averages of the results obtained were compared through the Tukey test at 5% probability. The conventional management was performed by means of the use of plow and grid, while the no-tillage management was characterized by sowing under remainders of the previous culture with no soil revolving. The denomination "no-tillage" was used in this experiment, but the parcel with no soil revolving does not characterize a continuous no-tillage system, once operations such as soil preparation aimed at eliminating the cotton stump and subsoiling for the elimination of compacted soil layers and redistribution of nutrients along the soil profile are periodically performed. Before the experiment was installed, soil non-deformed samples were collected with the aid of volumetric rings. The samples were led to the Soils Physics Laboratory of the Department of Natural Resources – Agricultural Sciences School, UNESP, Botucatu, Brazil, for the attainment of the water retention characteristic curve in relation to both soil managements adopted. Water was supplied to the culture by means of a central pivot irrigation system. Irrigation was monitored by means of three tensiometer batteries in each soil management treatment: conventional and no-tillage managements. Each battery was composed of two tensiometers installed at 15 and 30 cm of depth, where the first one defined the irrigation moment and the second one was used to control the amount of water applied (Saad & Libardi, 1992). The irrigations were performed whenever the average value read in tensiometer placed at 15 cm of depth reached 35 kPa (Silveira & Stone 1994; Moreira et al., 1999). For the determination of the soil cone index (soil mechanical resistance to penetration), a hydraulic-electronic penetrometer according to Lanças and Santos (1998) was used. The hydraulic-electronic penetrometer, assembled on a cart for haulage and application in tractors with hydraulic system, presents a cone with base area of 320 mm^2, solid angle of 30º and soil penetration constant velocity of 30 mm s^{-1} according to ASAE S313.2 (1991). The electronic system presents a data acquisition system (Microlloger 23X, Campbell), power sensor (load cell of 10000 N) and depth sensor (rotational potentiometer). The depths used for the determination of the soil cone index were 0-5; 5-10; 10-20 and 20-40cm in both treatments. The root development was evaluated when 50% of plants were found at full flowering stage and its sampling was performed using a galvanized steel auger with diameter of 4.5 cm. The soil collection for the root analysis occurred at days 3 and 4 of November in four layers (0-5; 5-10; 10-20 and 20-40cm). The samples were removed from the tillage line between one plant and another with four repetitions per parcel, summing up 52 samples from each layer per treatment. Later, the roots were separated from the soil through washing in running water with the aid of a 0.5 mm sieve. After separated and washed, the root samples were conditioned in universal collectors with alcohol solution 70% and placed into freezer at 4^{o}C. The variables that characterize the root development were determined in a Scanner coupled to a computer equipped with WinRhizo software, which uses the method proposed by Tennant (1975) as principle. This equipment determined length (Km m^{-3}), surface (m^2 m^{-3}) and root diameter (cm). After these evaluations, the samples were dried in stove at 65^{o}C until reaching constant weight for the determination of the root dry matter production (g m^{-3}). On the occasion of the bean culture harvest, 10 sequential plants in pre-determined site in the useful area of each parcel were collected, summing up 130 samples per treatment. These plants were led to the laboratory for the determination of the number of pod/plant, number of grains/plant, average number of grains/pod and mass of 100 grains, determined through random collection and weighting of two samples of 100 grains per parcel.

RESULTS AND DISCUSSION

The soil cone index values showed increase trend up to the layer of 10-20 cm for both treatments. In this layer, the highest values for no-tillage and conventional management systems were observed, 3254kPa and 3310kPa, respectively (Table 1). Physically, the root elongation is only possible when the root growth pressure is higher than the soil mechanical resistance to penetration (Passioura, 1991), which may be characterized by the soil cone index. According to Carvalho et al. (2006), the maximum soil cone index value for adequate root development in bean plants is of 2870 kPa, showing that values obtained were restrictive in layer of 10-20 cm. According to Canarache (1990), Arshad et al. (1996) and Merotto & Mundstock (1999), the soil cone index values found in this work can also be restrictive to the root development in most cultures.

Table 1**.** Soil cone index values (kPa) for no-tillage management (NM) and conventional management conditions (CM) at the different soil layers evaluated.

Soil Management	0-5cm	5-10cm	10-20cm	20-40cm
NM	1104	2736	3254	2335
CM	1095	3161	3310	2702

Thus, the bean plant root system was found at the most superficial soil layers (0-5cm and 5-10cm), presenting total length of 93% at the first 10 cm of the soil profile in the conventional management system and 84% in the no-tillage management system (Table 2). The most uniform root distribution in the no-tillage management system may be related to soil cone index values of layer 5-10 cm. In this layer, the soil cone index in the no-tillage management system (2736 kPa) was lower than that considered restrictive for this culture (2870 kPa), what was not observed for the conventional management system (3161 kPa). One yet observes that layers of 5-10 and 10-20 cm in the conventional management system presented values quite close to each other, 3161kPa and 3310kPa respectively, what might have been caused by adjustment problems of the agricultural accessories work effective depth, thus evidencing alterations at the depth of the compacted subsuperficial layers.

Table 2**.** Distribution of the bean plant root length along the soil profile at no-tillage (NM) and conventional (CM) management systems for depths evaluated.

Soil layer (cm)	NM	CM
0-5	38%	61%
5-10	46%	32%
10-20	11%	6%
20-40	5%	1%

The layer of 5-10 cm also presented significant differences in the dry weight of roots (Table 3), of 898.35 $g.m^{-3}$ in the no-tillage management system and of 598.59 $g.m^{-3}$ in the conventional management system. For the other root development variables, no significant differences between treatments were observed. The most uniform root distribution results in no-tillage management are not in agreement with Stone & Silveira (1999), who obtained better distribution in plow-prepared soil.

Table 3**.** Length ($km\ m^{-3}$), surface ($m^2\ m^{-3}$), dry weight ($g\ m^{-3}$) and root diameter (cm) of the bean plant in no-tillage management system (NM) and conventional management system (CM) at the different layers evaluated.

Soil layer (cm)	Length ($km\ m^{-3}$)		Surface ($m^2\ m^{-3}$)		Dry Weight ($g\ m^{-3}$)		Diameter (cm)	
	NM	CM	NM	CM	NM	CM	NM	CM
0-5	9,04a	16,66a	14,37a	22,35a	733,15a	924,55a	0,054a	0,046a
5-10	10,98a	8,67a	19,93a	11,82a	898,35a	598,59b	0,059a	0,048a
10-20	2,68a	1,53a	5,28a	3,26a	339,38a	263,67a	0,056a	0,059a
20-40	1,11a	0,28a	1,72a	0,44a	93,53a	74,70a	0,048a	0,042a

Values followed by same letter are not significantly different at 5% probability through the Tukey test.

However, distribution differences in the root system and dry weight of roots were not sufficient to influence the bean yield of bean plants between treatments (Table 4). These results are similar to those obtained by Mullins et al. (1980) and Zafarroni et al. (1991), who also found differences in bean yield between no-tillage and conventional management systems.

Table 4**.** Number of grains per plant, pod per plant, grains per pod, mass of 100 grains and bean yield in function of the different soil preparations, conventional management (CM) and no-tillage management system (NM).

Soil management	Grains/plant	Pod/plant	Grains/pod	Mass of 100 grains (g)	Bean Yield (Kg ha^{-1})
NM	83,48a	15,22a	5,14a	18,02[a]	3360a
CM	78,41a	16,22a	5,16a	19,47[a]	3330a

Values followed by same letter are not significantly different at 5% probability through the Tukey test.

CONCLUSIONS

The root system distribution in the 0-40cm layer was more uniform in no-tillage management system in relation to the conventional one. The no-tillage management system presented higher root dry weight value than the conventional management system at layer of 5-10 cm. No significant difference in relation to bean yield between soil managements evaluated was observed.

BIBLIOGRAPHIC REFERENCES

Arf, O., Rodrigues, R. A. F., Sá, M. E., Buzetti, S., Nascimento, V. Manejo do solo, água e nitrogênio no cultivo de feijão. Pesquisa Agropecuária Brasileira, Brasília, v.39, n.2, p.131-138, 2004.

Arshad, M.A.; Lowery, B. & Grossman, B. Physical tests for monitoring soil quality. In: DORAN, J.W. & JONES, A.J., eds. Methods for assessing soil quality. Madison, Soil Science Society of America, 1996. p.123-141 (SSSA Special publication, 49).

ASAE Standard ASAE S313.2, Soil Cone Penetrometer, Agricultural Engineers Yearbook of Standards, American Society of Agricultural Engineers, St. Joseph, Michigan, EUA, 591 p., 1991.

Campos, R.C.; Reinert, D.J.; Nicolodi, R.; Ruedell, J.& Petrere, C. Estabilidade estrutural de um Latossolo Vermelho-Escuro distrófico após sete anos de rotação de culturas e sistemas de manejo do solo. Revista Brasileira de Ciências do Solo, v.19, p.121-126, 1995.

Canarache, A. Penetr-a generalized semi-empirical model estimating soil resistence to penetration. Soil Till. Res., v.16, p.51-70, 1990.

Carvalho, G. J., Carvalho, M. P., Freddi, O. S., Martins M. V. Correlação da produtividade do feijão com a resistência à penetração do solo sob plantio direto. Revista Brasileira de Engenharia Agrícola e Ambiental, v.10, n.3, p.765–771, 2006.

Chan, K.Y.; Roberts, W.P.; Heeman, O.F. Organic carbon and associated soil properties of a red earth after 10 years of rotation under different stubble and tillage practices. Australian Journal of Soil Research, Melbourne, v.30, p.71-83, 1992.

Freddi, O. S., Carvalho, M. P., Júnior, V. V., Carvalho, G.J. Produtividade do milho relacionada com a resistência mecânica à penetração do solo sob preparo convencional. Engenharia Agrícola, Jaboticabal, v.26, n.1, p.113-121, 2006.

Klein, V.A., Libardi, P.L. Armazenagem de água no solo e resistência à penetração. In: REUNIÃO BRASILEIRA DE MANEJO E CONSERVAÇÃO DO SOLO E DA ÁGUA, 12. 1998. Fortaleza/Ceará. Resumos expandidos. Sociedade Brasileira Ciências do Solo. Universidade Federal do Ceará. p.163-164. 1998.

Knavel, D.E.; Herron, J.W. Response of vegetable crops to nitrogen rates in tillage systems with and without vetch and ryegrass. Journal of the American Society of Horticultural Science, Alexandria, v.111, n.4, p.502-507, 1986.

Lanças, K. P., Santos Filho, C.A. Penetrômetro hidráulico-eletrônico equipado com DGPS para avaliação da compactação do solo. La Plata, Editorial de la U.N.L.P. p.570-576. 1998.

Lopes, A. S.; Pavani, L.C.; Corá, J. E.; Zanini,J.R.; Miranda, H.A. Manejo da irrigação (tensiometria e balanço hídrico climatológico) para a cultura do feijoeiro em sistemas de cultivo direto e convencional. Engenharia Agrícola, Jaboticabal, v.24, n.1, p.89-100, 2004.

Merotto, A. & Mundstock, C.M. Wheat root growth as affected by soil strength. Revista Brasileira de Ciência do Solo, v.23 p.197-202, 1999.

Moreira, J.A.A., Stone, L.F., Silva, S.C., Silveira, P.M. Irrigação do feijoeiro no sistema plantio direto. Santo Antônio de Goiás: Embrapa Arroz e Feijão, p. 31, 1999. (Embrapa Arroz e Feijão. Circular Técnico, 33).

Mullins, C.A.; Straw, R.A. Production of snap beans as affected by soil tillage method and row spacing. Journal of the American Society of Horticultural Science, Alexandria, v.113, n.5, p.667-669, 1988.

Mullins, C.A.; Tompkins, F.D.; Parks, W.L. Effects of tillage methods on soil nutrient distribution, plant nutrient absorption, stand, and yield of snap beans and lima beans. Journal of the American Society of Horticultural Science, Alexandria, v.105, p.591-593, 1980.

Passioura, J. B. Soil structure and plant growth. Australian Journal of Soil Research, Collingwood, v. 29, p. 717-728, 1991.

Pedroso, P.A.C.; Corsini, P.C. Manejo físico do solo. In: FERREIRA, M.E., YAMADA, T.; MALAVOLTA,E. Cultura do arroz de sequeiro: fatores afetando a produtividade. Piracicaba: Associação Brasileira para a pesquisa da potassa e do fosfato, 1983. p.225-238.

Richther, D.D.; Barbar, L.I.; Huston, M.A.; Jaeger, M. Effects of annual tillage on organic carbon in a fine-textured udalf: the importance of root dynamics to soil carbon storage. Soil Science, Baltimore, v.48, n.3, p.78-83, 1990.

Saad, A.M.; Libardi, P.L. Uso prático do tensiômetro pelo agricultor irrigante. São Paulo: IPT, p.27, 1992.

Sampaio, G.V.; Galvão, J.D.; Fontes, L.A.N.; Figueiredo, M. S.; Cardoso, A.A. Efeitos de sistemas de preparo do solo sobre o consórcio milho-feijão (Phaseolus vulgaris L.). Revista Ceres, Viçosa, v.36, p.465-482, 1989.

Silva, A.P., Libardi, P.L., Camargo, O.A. Influência da compactação nas propriedades físicas de dois Latossolos. Revista Brasileira de Ciência do Solo, 10:91-95, 1986.

Silveira Neto, A. N., Silveira, P. M., Stone, L. F., Oliveira, L. F. C. Efeito de manejo e rotação de culturas em atributos físicos do solo. Pesquisa Agropecuária Tropical, v.36, n.1, p.29-35, 2006.

Silveira, P. M. da, F. J. P. Zimmermann & A. M. do Amaral.. Efeito da sucessão de cultura e do preparo do solo sobre o rendimento do arroz de sequeiro. Pesquisa Agropecuária. Brasileira, v.33, n.6, p. 885-890, 1998.

Silveira, P.M.; Stone, L. F. Manejo da irrigação do feijoeiro: uso do tensiômetro e avaliação do desempenho do pivô central. Goiânia: EMBRAPA, p.46 1994. (Circular Técnico, 27).

Siqueira, N. de S. Efeitos de sistemas de preparo do solo sobre a cultura do feijoeiro (Phaseolus vulgaris L.) e sobre algumas propriedades físicas e químicas do solo. Viçosa: UFV, 1989. 106p. Tese de Mestrado.

Stone, L. F. Efeito de lâminas de irrigação e preparo do solo na resposta do feijoeiro ao nitrogênio em cobertura. Santo Antônio de Goiás: Embrapa Arroz e Feijão, 2002. 24p.

Stone, L. F.; Moreira, J.A.A. Efeito de sistemas de preparo do solo no uso da água e na produtividade do feijoeiro. Pesquisa Agropecuária Brasileira, v.35, n.4, p.835-841, 2000.

Stone, L. F.; Silveira, P. M. Efeito do sistema de preparo na compactação do solo, disponibilidade hídrica e comportamento do feijoeiro. Pesquisa Agropecuária Brasileira, v.34, p.83-91, 1999.

Stone, L.F.; Moreira, J.A.A. Resposta do feijoeiro ao nitrogênio em cobertura, sob diferentes lâminas de irrigação e preparos do solo. Pesquisa Agropecuária Brasileira, Brasília, v.36, m.3, p.473-481, 2001.

Tennant, D. A test of a modified line intersect method of estimating root length. Journal of Ecology, v.63, p.995-1001, 1975.

Wutke, E.B.; Arruda, F.B.; Fancelli, A.L.; Pereira, J.C.V.N.A.; Sakai, E.; Fujiwara, M.; Ambrosano, G.M.B. Propriedades do solo e sistema radicular do feijoeiro irrigado em rotação de culturas. Revista Brasileira de Ciência do Solo, Viçosa, v.24, n.3, p.621-33, 2000.

Zaffaroni, E.; Barros, H.H.A.; Nóbrega, J.A.M.; Lacerda, J.T.; Souza Junior, V.E. Efeito de métodos de preparo do solo na produtividade e outras características agronômicas de milho e feijão no Nordeste do Brasil. Revista Brasileira de Ciência do Solo. Campinas, v.15, n.1, p.99-104, 1991.

CAN FROST DAMAGE IMPACT WATER DEMAND FOR CROP PRODUCTION IN THE FUTURE?

Michel Baraer[1]
Chandra A. Madramootoo[2]

ABSTRACT

One of the most efficient techniques used to protect the buds, flowers, and fruits of apple trees against potentially damaging spring frosts, is by spraying irrigation water on the fruit trees via a sprinkler irrigation system. The purpose of this study was to evaluate the impacts of global warming on frost occurrences for the fruit growing conditions in Québec, with the long-term objective being to evaluate how this will alter amounts of water used for frost protection. Frost injury risk is characterized by using a phenological model coupled with a risk index generator. The phenological model was selected amongst a group of models for its ability to maintain a satisfactory level of accuracy when tested under different climatic conditions. Based on meteorological and phenological observations on apple trees in the Monteregie region of Québec, the model calibration and validations provided evidence of the ability of the selected model to reproduce and predict frost injury risk trends. Local climatic conditions downscaled from a GCM were used to assess the effects of future climate scenarios on the risk of frost injuries. Under the tested scenario, the risk index increases significantly, suggesting that the number and / or the severity of spring frost injuries would increase in the future. This would imply that the use of a sprinkler system as a protection method against frost injuries has to be taken into consideration for the assessment of climate change impacts on overall water demands for crop water requirements.

INTRODUCTION

Spring frost injuries sometimes negatively affect annual fruit production in Canada. In Québec orchards, major frost occurs once every 10 years on average, impacting up to 40% of the annual crop yield. Milder events occur more frequently but are not systematically recorded. Between 1961 and 1986, a significant reduction in harvest due to spring frost injuries was apparent five times (Charette and Krueger, 1992). Taken individually, they might represent an important financial loss for the producers. According to the Fédération des producteurs de pommes du Québec, the total provincial revenue at the farm level for apple production in Québec was up to $33.8 million in 2003, representing around 22% of the Canadian production. Therefore, frost damage can lead to a significant economic loss at the provincial level as well. Several protection methods exist for producers to avoid or limit the effects of spring frost on their production. Among the most frequently recommended is sprinkler irrigation. It exhibits advantages other protection methods cannot provide such as the low energy costs and the dual-purpose of the

[1] MScA Candidate; Brace Center for Water Resources Management, Faculty of Agricultural and Environmental Sciences, McGill University, 21111 Lakeshore Road, Montreal, Québec H9X 3V9; Michel.Baraer@mail.mcgill.ca
[2] Dean of the Faculty of Agricultural and Environmental Sciences and Director of the Brace Center for Water Resources Management, McGill University, 21111 Lakeshore Road, Montreal, Québec H9X 3V9; Chandra.Madramootoo@mcgill.ca

equipment (summer irrigation and spring frost protection). In addition, sprinkler protection has the potential to protect against some advective frosts while other methods such as wind machines or helicopters are applicable to radiation frosts only. Though specific disadvantages are also related to the use of sprinkler under negative temperatures, some consider sprinkler irrigation as the most attractive method for plants and trees frost protection (Koc et al., 2000; Jolivet, 2006).

From an environmental point of view, water consumption represents the most important drawback of sprinkler irrigation for protection against frost. Snyder and De Melo-Abreu (2005) recommended an application of 2.5 to 5.8 mm h^{-1} of water depending on the meteorological conditions. These rates lead to an annual water consumption of 1000 to 3000m^3 yr^{-1} ha^{-1} for 6 frost protection utilizations, each of 10 hours duration. This consumption level represents a significant threat for water availability. The National Water Research Institute of Canada observed that irrigation use for frost protection is increasing and that this practice further stresses water resources (NWRI, 2003). In a context of increasing competition between water users, this trend on water demand needs to be further analysed.

The purpose of this study was to make predictions on climate change impacts for damaging frost occurrences in Québec, with the long term objective to facilitate the evaluation of the impact it could have on water demands. Apple production represents the dominant fruit growing activity in Québec. Therefore it has been selected to be the reference crop for this research.

The conditions that lead to a spring frost injury are directly related to the phenological stage of the tree. If exposed to a temperature of -4°C for more than 30 minutes, a blooming bud will not survive, while if exposed during the first step of its development, the buds are not affected.

This means that a study on the impact of climate change on frost injuries has to cover both the prediction of future spring minimum daily temperatures as well as temperature change on the bud development process. The relation that exists between climate variations and the phenology of plants is described by Schwartz and Reiter (2000) who have observed an average advance of five to six days toward earlier springs in North America over a 35-year period from 1959-1993. Wolfe (2005) also observed an advance in spring weather conditions, with a slope for mid-bloom date versus year of -0.2 day/year, which is qualitatively consistent with a warming trend. His analysis was based on phenological observations between 1965 and 2001 on different horticultural species, including apple trees, in North-Eastern US. Since the early 1990’s, phenological models predicting the timing of budburst of trees are regularly used to predict the effects of climate change on tree phenology. On the other hand, as available phenological models are suspected of not being adapted for climate change studies, consequences of global climate change on phenology remain controversial (Chuine 2000). Hanninen (1995) tested 96 models on both natural conditions and on semi-controlled conditions simulating climate change. He found that Degree-Day models (DD) provided good results in predicting the phenological events under natural conditions, but failed by about 70 days in predicting the phenology under the climate change simulation. Linkosalo (2000) also found that temperature based models, even if they are widely applied to phenological research, provide predictions that are quite different than the ones from light-climate triggered models. His conclusion was that light-climate models should be used for climate warming studies. On the other hand, a large number of studies, even the most recent ones, consider climate based models for use under global warming conditions. Zinoni (2004) proposed a chilling-forcing model for apple trees to study climate change effects on Italian agriculture. Picard (2005) tested four phenological models for bud-burst prediction in Siberia and concluded that among the tested models, the simplest DD model was found to perform just as well as more complex models accounting for a chilling requirement. The contradicting results of these different studies highlight the need for specific attention to the selection of an appropriate phonologic model.

METHODOLOGY

Phenological models

The models selected for this study strive to be representative of the three different model types that are most often recommended for phenological development prediction: the simple degree-day models; the chilling-forcing models; and the light-temperature models.
The Degree-Day models are among the most commonly used and simplest models designed for phenology stage prediction. They are based on the concept that the air temperature at the growth period is the most significant factor triggering bud development. The Degree-Day model (DD) used for this study, starts accumulating at 32 days.
The chilling–forcing models (CF) cover two physiological stages of trees: the dormancy period and the growing period. The CF model, selected for this study, is an adaptation of the “Chill” model developed by Cesaraccio (2005). It is a chill/anti-chill day’s model that corresponds to an improved version of a temperature based sequential chilling-forcing model. This model has shown the best performance in predicting the phenological stages of 22 different crops when compared with seven other models tested under similar conditions. In addition, the “Chill” model has been described as being the best model for application onto apple trees by Zinoni (2004). The CF model differs from the Chill model by having a fixed harvest date and by being adapted to very cold winters.

In light-temperature models (LT) both daylight and temperature are used as predictors for bud development stages prediction. In total three light-temperature models are employed in this study, two are based on published models, LT3 and LT6, and one has been developed for this project, LT5.

LT3 is based on a model designed for the prediction of the flowering time for the Narrow-leafed Lupin (Reader et al., 1995). The model adaptation consists of fixing the day of calculation starting on February 1 (sowing date in the original model). In order to improve the accuracy of the predictions, mean daily temperature is considered when larger than +5°C only.

LT5 uses daily irradiance and mean temperature as its driving parameters. As a degree-day model, it accumulates units of temperature when these exceed a given threshold. In addition, units of light, represented by the daily irradiance, are systematically accumulated from February 1. The model is described by the following equations:

$$\begin{cases} \text{if } \overline{T}_j < Tc \text{ then } LT_j = bL_j \\ \text{if } \overline{T}_j \geq Tc \text{ then } LT_j = a\overline{T}_j - Tc + bL_j \end{cases} \quad (4)$$

$$\text{and}: \quad \sum_{j=k}^{n} LT_j \geq TLD \quad (5)$$

Where T_j *bar* (°C) is the daily mean temperature, L_j (KWh/m^2) is the irradiance value, T_c is a temperature threshold and LT_j represents the daily heat and radiation accumulation. The day that corresponds to the phenological event, *n*, is defined as the moment when the units accumulation LT_j becomes larger than a given threshold, TLD. *a* and *b*, are crop and site related parameters.

Finally, LT6 is a model described as the one providing the most accurate results under climate change conditions by Hanninen (1994) in a test of 96 models. Its application to apple tree phenology does not require specific adaptation.

Area and crop

The phenological models described above are applicable to different crops and cultivars. However this study is limited to the McIntosh Apple, the most frequently observed apple cultivar in Québec. Seven phenological stages are considered: Green tip (S1); Half-inch Green (S2); Tight Cluster (S3); First Pink (S4); Full Pink (S5); Full Bloom (S6) and Calices (S7). Phenological models require temperature data sets that cover more than just the growing period. They are therefore calibrated using meteorological parameters from nearby stations.

The study focuses on the largest apple production area in Québec, the Montérégie. Simulations were conducted for three different sites: Rougemont, Farnham and Freligsbourg (Figure 1). The Farnham station (45°15'N; 72°58'O) time series are used to calibrate phenological models at Farnham and Rougemont (45°25'N; 73°6'O) while the time series from Brome (45°10'N; 72°34'O) serve as calibration data for Freligsbourg (45°3'N; 72°52'O). Details on data sets used are given in Table 1.

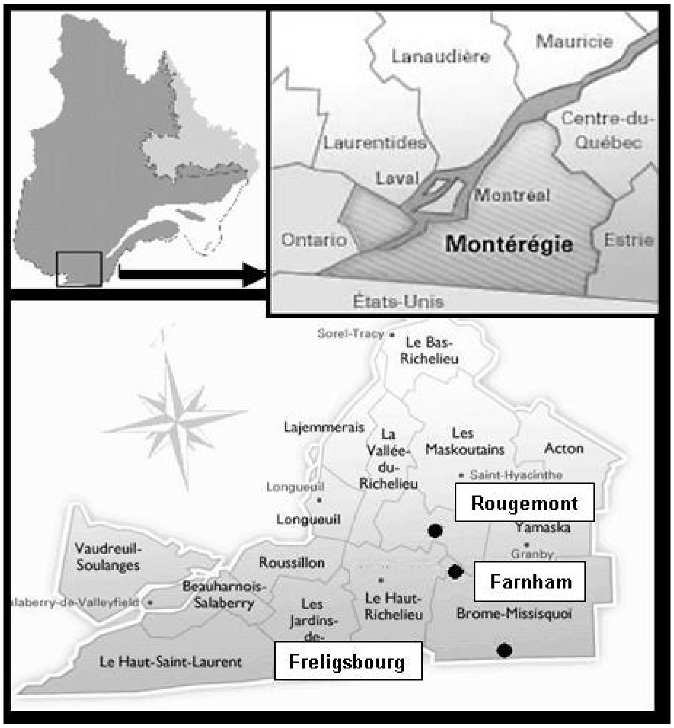


Figure 1. Map of Montérégie & location of the three experimental sites.

Table 1. Description of the used observation time series

Type	Location	Use	# of years	Period
Phenology all stages[3]	Farnham	calibration and validation V1	28	1960-1988
Phenology all stages[3]	Rougemont	calibration and validation V1	28	1977-2005
Phenology all stages[3]	Freligsbourg	calibration and validation V1	27	1977-2004
Phenology S7	Monteregy av.	Validation phase V2		1926-1950
Phenology S7[3]	6 sites, Montegerie	Statistical tests	26	1979-2005
Station T°	Farnham	calibration and downscaling	48	1926-2001
Station T°	Brome	calibration and downscaling	51	1926-2005
Orchard T°[3]	Farnham	Tcrit module	16	1972-1988
Orchard T°[3]	Rougemont	Tcrit module	22	1972-1995
Orchard T°[3]	Freligsbourg	Tcrit module	20	1972-1995
Daylight	All	LT3 & LT6 models	85	1920-2005
Solar radiations	regional	LT5 model	averaged	-

Model selection procedure

There are three basic requirements a phenological model should meet in order to be used for a climate change impact study. First, the selected model should demonstrate a good ability in reproducing phenological events observed on a period adjacent to the calibration data time series. Secondly, the model should be able to reproduce observed phenological events that are distant enough from the calibration period to be representative of climate change conditions. At this stage, the model should not show signs of systematic susceptibility to changes in climatic

[3] IRDA: Institut de recherche et de développement en agroenvironnement/ Réseau-pommier du Québec

conditions. Finally, the model should consistently provide realistic predictions under climate forcing simulations. For example, no odd predictions such as bud burst being predicted before the pink tips, phenological stage not being predicted at all, or the model showing error messages should not be observed. Presently, phenological models are evaluated for these criteria through two validations phases called V1 and V2 and through a screening of individual predictions obtained under the climate change scenario. The first validation step, (V1) covers recent observations while V2 is based on a set of phenological observations that were recorded in the first half of the last century. The oldest time series are given for the whole production region, not for individual stations. It is assumed that the regional observations are equivalent to the mean of observations from six well spread out sites. This average of six sites being very well correlated with the mean of the three pilot stations (correlation coefficient = 0,996), this value is accepted to represent the regional observation. V2 is performed for the full bloom stage, S7, only. The root mean square error, *Re*, is the primary parameter used for the models calibration. The calculation of the coefficient of determination, R^2, completes the utilisation of the root mean square error for the models evaluation at the different validation phases. A third indicator is introduced at the validation phase V2, called S_b. It measures eventual systematic bias in model predictions, and is defined as follows:

$$S_b = \frac{\left(\sum_{i=1}^{n} D_{V2pred} - \sum_{i=}^{n} D_{V2obs}\right)}{n} + \frac{\left(\sum_{j=1}^{m} D_{V1obs} - \sum_{j=1}^{m} D_{V1pred}\right)}{m} \quad (10)$$

Where *n* and *m* are the number of predictions made on the V2 and V1 periods respectively and *D* is the yearly full bloom date predicted (pred) or observed (obs) during the period of V1 or V2.

Tcrit model

The risk of spring frost injury is characterised on a yearly basis by frost index *I*. It represents the severity of the most harmful events predicted during the year. Each predicted frost event is rated on a scale from 0 to 4; 0 representing no risk of injury, 4 a risk of severe damages.
In order to identify the risk related to an event, the index calculation module, called Tcrit, bases its index ranking calculation on four threshold levels. Wees (2001) published lethal temperatures, LT_{10} and LT_{90} (temperatures at which 10 and 90 percent of the buds are destroyed), associated with the bud growth stages for apple trees in Québec. These temperatures combined with predicted phenological phases are, in the present study, used as moving thresholds to characterise the injury risk related to projected daily minimum temperatures. Each time the minimum temperature reaches a threshold line an individual frost event is ranked from 1 to 4. Tcrit then converts the annual frost events ranked in a yearly spring frost index. The threshold calculation for each phenological stage is illustrated in Figure 2. Ranking limits for days that stand between two phenological stage times are calculated by assuming a linear trend for the lethal temperatures between two phenological events.

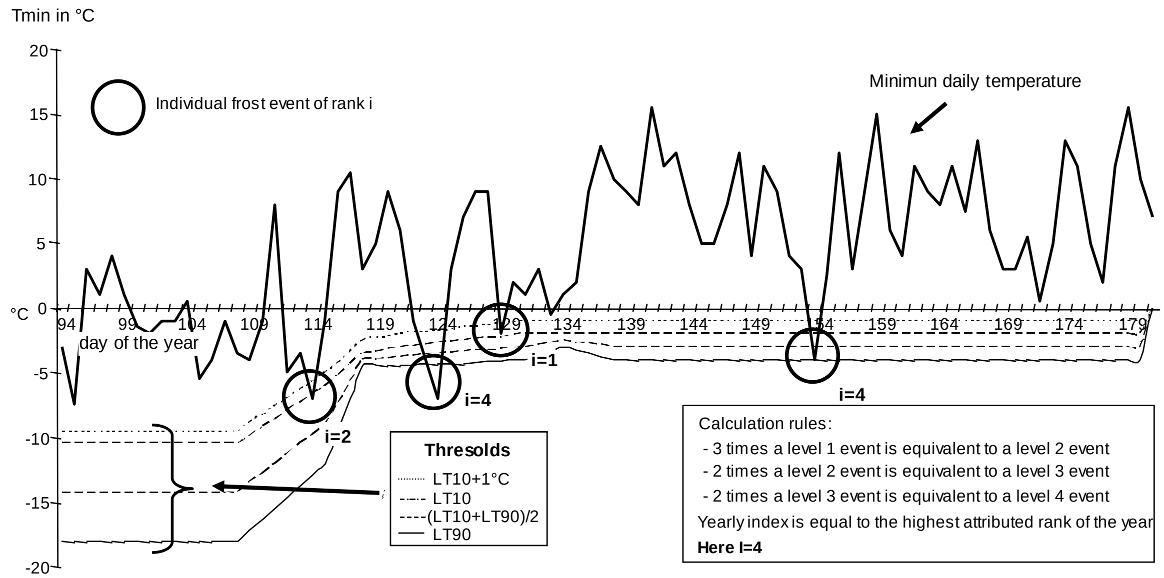


Figure 2. Tcrit module calculation principle.

Coupled with a phenological model, Tcrit provides an easy to use yearly indicator, which is used in this study to identify eventual trends in spring frost injury risks for the present century.

Climate change scenario

Projections of future climatic conditions originate from the Canadian Global Circulation Model called CGCM1, run under the IPCC scenario IS92a. Minimum, maximum and average temperatures at the three different sites of interest are obtained through downscaling. LARS-WG, a stochastic weather generator, is the downscaling tool that was selected to generate temperature predictions at the station level. For each downscaled climatic parameter, two-thirds of the collected measures are used for model calibration.

Four different periods representing four different climatic conditions were considered during downscaling: 1970-1999; 2010-2039; 2040-2069; 2070-2099. These periods cover 30 years of homogeneous climatic conditions. This means that the differences between yearly climatic conditions within a period are random. For example, the meteorological projections for the years 2010 and 2039 are based on the same climatic assumptions while the differences between the years 2039 and 2040 are both due to randomness and to climatic forcing. This is the reason why all model outputs related to climatic projections are presented as period averages rather than as single year results.

RESULTS

Climate change effects observations

The effect of global warming between the two validation periods V1 and V2 is verified through a multivariate Mann-Kendall trend analysis on the growing period daily mean temperatures

(March, April, May) and on the regional mean full bloom date for the period 1926-2005. The standardized test statistic MK Stat shows a significant positive trend for the growing period average temperature (MK stat = 2.3 with a p-value = 0.021) and a significant negative trend for the full bloom date (MK stat = -2.21 with a p-value = 0.027). Between 1926-1950 and 1979-2005 there is a 0.97°C increase in the average growing season daily temperatures while the regional full-bloom date is advanced by 4.36 days on the time interval.

The change in the apple tree phenology between the two periods corresponds to an average rate of -0.08 day/year. This value is situated below figures reported by Schwartz and Reiter (2000), or by Wolfe (2005), respectively at -0.16 day/year and at -0.2 day/year.

Model validation V1

The calibration is performed for each phenological stage, each site and model. Every model is associated with a cluster of 21 different sets up that are challenged during the validation stages. Results from this phase are presented in Figure 3. Most of the models exhibit a strong ability to reproduce contemporary observations.

The coefficient of determination R^2 for all models excepted for LT3, are over 0.9. This performance is confirmed by the root mean square error. All models have a *Re* median lower than 4 days and a Q_{75} quartile below 5 days. LT3, the less accurate model at this stage, is the only one presenting outliners over 7 days. LT5 and LT6 are here the most accurate models. LT6 shows both the best R^2 and *Re* values. For comparison, Hanninen (1994) reached a *Re* of 4.1 days with the similar model on a shorter period of observation.

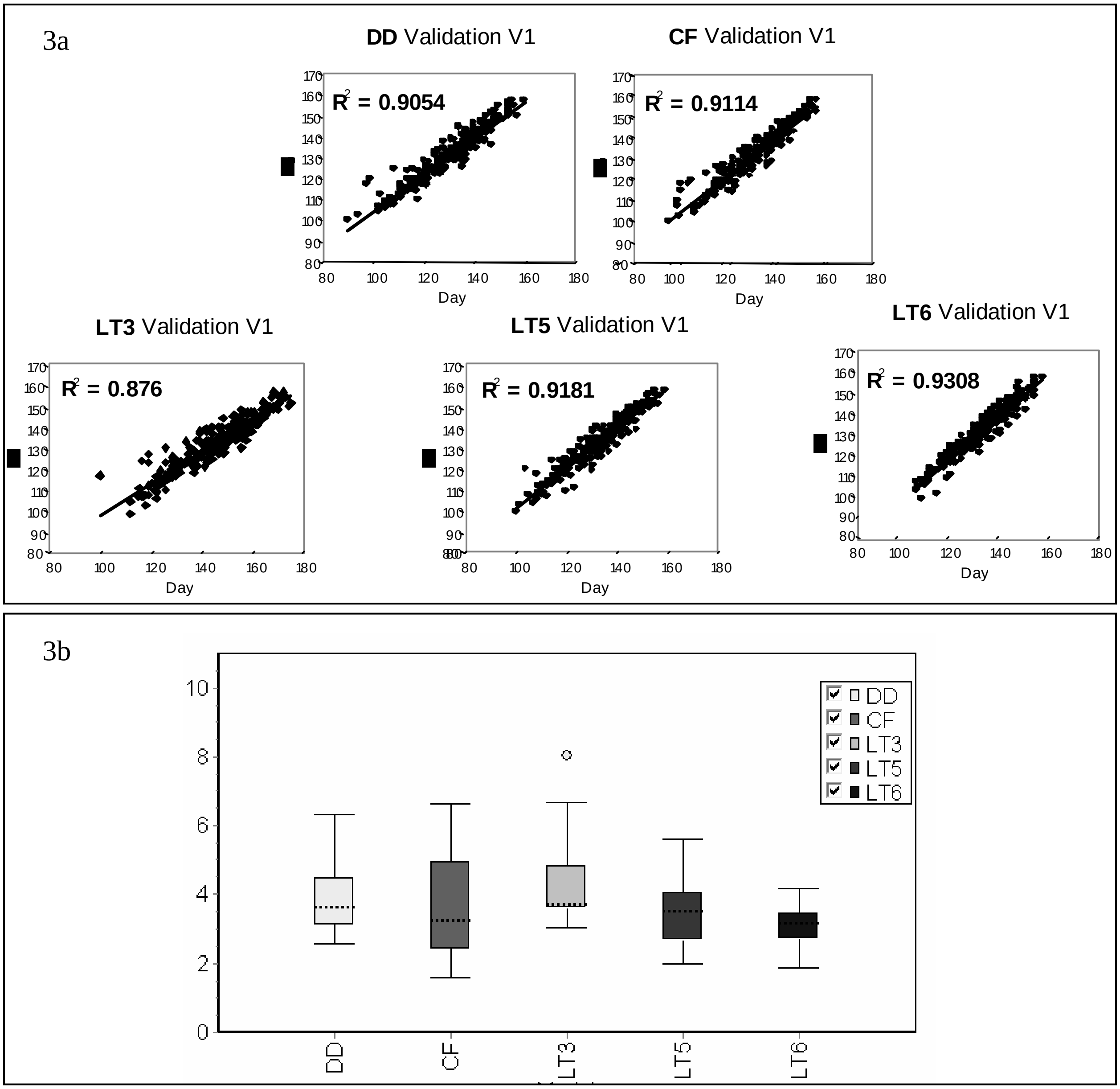


Figure 3. V1 Validation results.3a: Scatter plot of observed versus predicted values and coefficient of determination results; 3b: Box plot of roots mean square errors, the dotted line represents the median value, the box materialises the inter quartile range (IQR), the whisker is the min or max value that stands within the 1.5 *IQR* value, spots are outliners.

Models validations V2

Old phenological observations are not guaranteed to be as reliable as the recent ones and care should be used in V2 result analysis. The three performance indicators calculated for each model are presented in Figure 4. This chart suggest that both the DD and the LT3 models could be susceptible to change in climatic parameters as both of them present a systematic bias indicator close to one day. In addition both the *Re* and *R2* values for the DD model are the weakest observed. Here again the LT5 and LT6 models exhibit good results. LT5, by reaching the best value for each of the three indicators, comes out as the most adapted model for uses under climate change conditions.

Climatic predictions

As for the phenological model, the downscaling tool is calibrated for two thirds of the meteorological observations and validated for the remaining part. For each station three meteorological parameters are extracted: Tmin, Tmean and Tmax, respectively, the monthly average of daily minimum, average and maximum temperatures. The predicted monthly minimum average temperatures for the four considered time periods: 1972-200l; 2010-2039; 2040-2069 and 2070-2099 are presented in Figure 5.

The increase of the yearly temperatures predicted by the model between periods 1972-2000 and 2070-2099, +4.55°C, is unevenly distributed across the year. For the first six months of the year, the most important period for apple tree phenology, the most significant temperature increase between 1972-2000 and 2070-2099 is + 8.9°C predicted for the month of February, while the smallest temperature deference would be observed in April with a difference of +3°C.

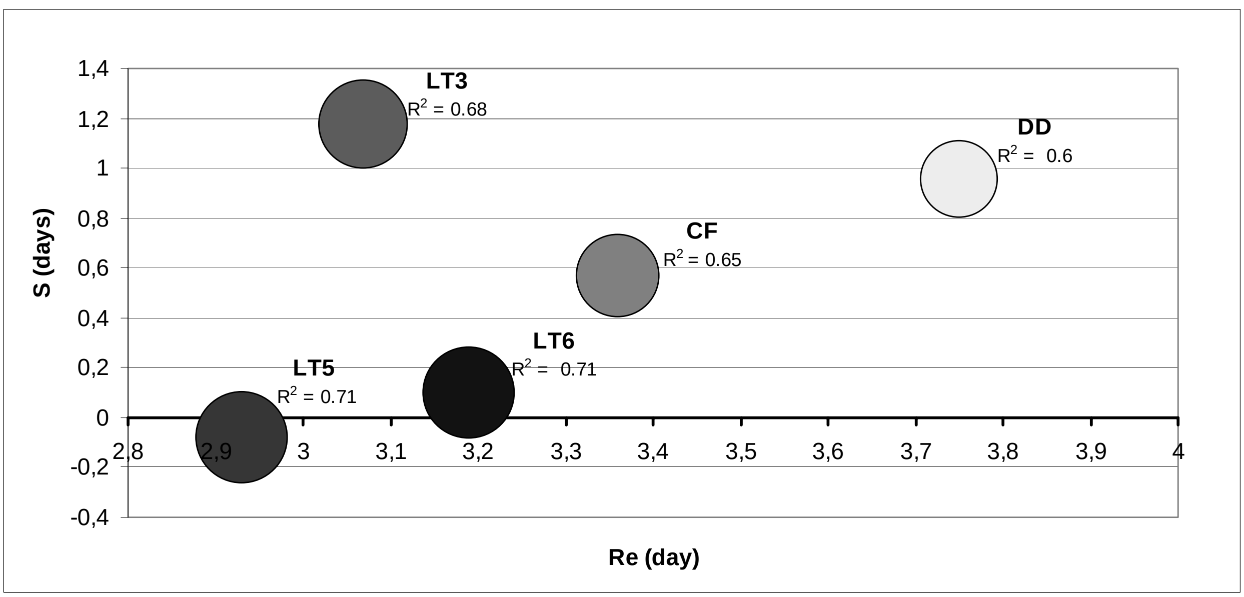


Figure 4. Bubble chart of the model performance indicator at V2 stage. The size of the bubbles represent the coefficient of determination, the x axis stands for the roots mean square error while the systematic bias parameter is read on the y axe. Models that exhibit large bubbles, low *Re* and S_b close to the 0 line perform well under V2 conditions.

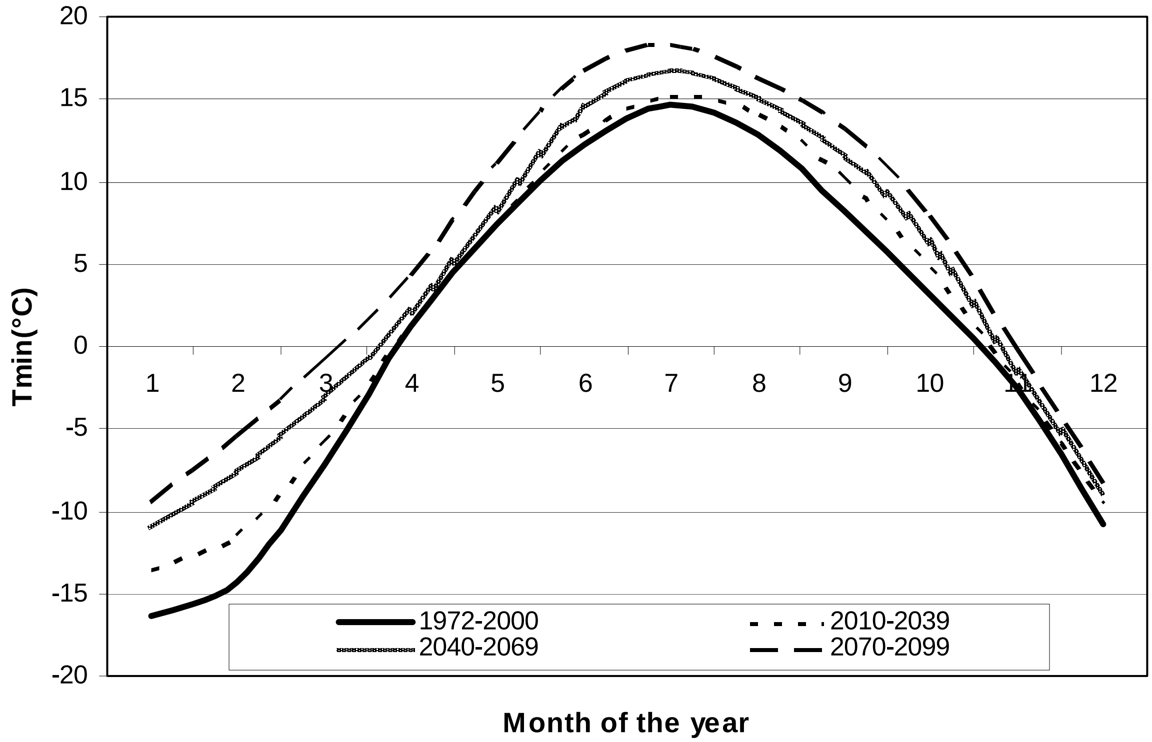


Figure 5. Evolution of the monthly average of minimum temperatures as predicted under downscaling conditions (1972-2000 based on simulated data).

Phenological models response to climatic scenarios

Two phenological models produce a significant number of wrong predictions under climatic forcing conditions. LT3 is the most unstable of the models with an average 10% of odd values generated. This percentage is low for the period 2010-2039 and increases with time. For the period 2070-2099 almost all years are affected by wrong predictions for one or more phenological stages. The CF model does not demonstrate an acceptable ability to be used under long term climate change predictions either. The proportion of generated errors is negligible during the periods 2010-2039 and 2040-2069, and it reaches almost 50% in the years for the period 2070-2099. Other models do not generate significant proportions of odd values under the predicted conditions. Average phenological projections under climate change predictions are presented in Figure 6 for these three models. As suggested during the validation phase V2, the DD model reacts more to change in climatic parameters than the two remaining LT models: excepted for the last phenological stages, the DD models predict the different stages in average two to three days earlier than the LT models. The systematic difference in prediction is particularly large for the first development stages. The three models do not predict an important change in apple tree phenological behaviour between the periods 1972-2000 and 2010-2039. The shift in phenological event dates is much stronger from the period 2040-2069 and 2070-2099, reaching almost 20 days for the latest events.

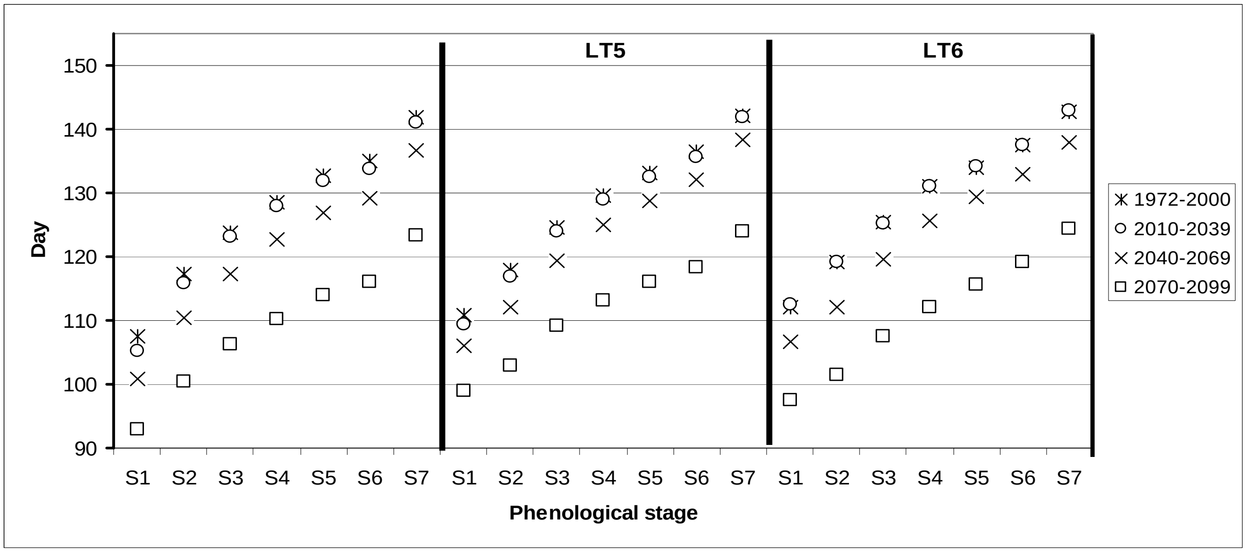


Figure 6. Average phenological events prediction for the different time-periods for DD. LT5 and LT6 models.

LT5 and LT6 are the models that demonstrate the best ability to fit with requirements that were stated for the model selection process. These two models only are utilised for the final part of the study.

Frost injury risk index projections

The phenological projection obtained through models LT5 and LT6 are introduced into the Tcrit model, which generates a frost injury risk index for each year and for each site. Yearly station related indexes are then compiled into a time period regional average index. The resulting values are shown in Figure 7.

There is a clear positive trend in the index regardless of which one of the two phenological models are used. This means that under the study conditions, the Tcrit model predicts an increase in frost injury risk for the 21st century. The difference between the LT5 and LT6 based projections is neglectable for the 2040-2069 and 2070-2099 periods. On the 2010-2039 time period, the use of LT6 suggests a negligible change in damaging frost occurrence while the LT5 based predictions show a slight risk of increase for the first time period.

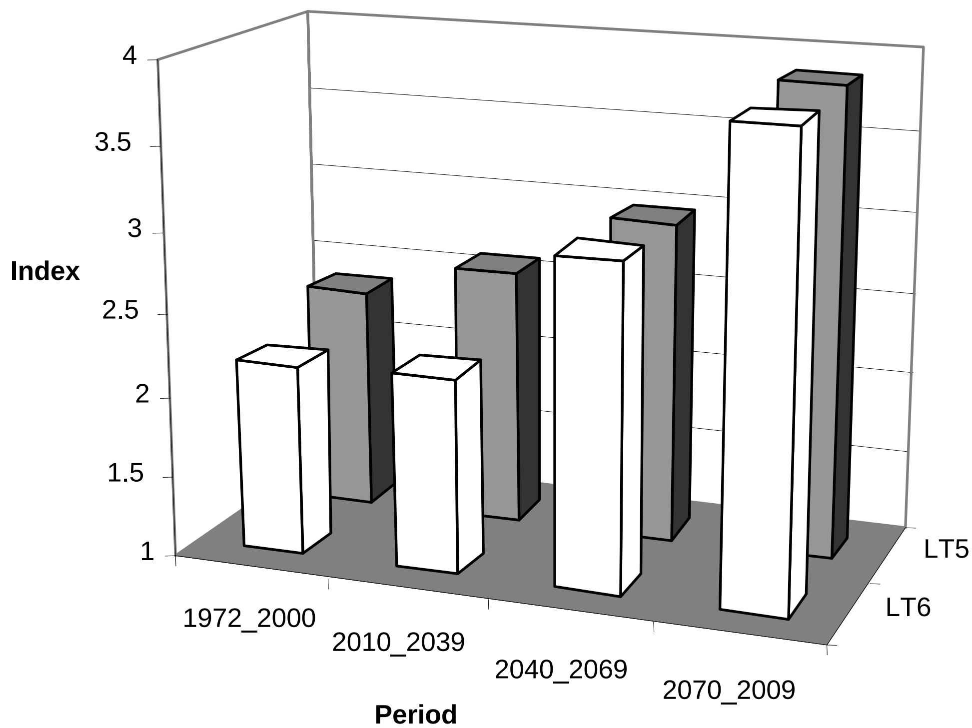


Figure 7. LT5 and LT6 based spring frost injury risk index projection for the 21st century

DISCUSSION

Climate change impact prediction studies are all dependant on the reliability of climatic projection. This is the case in this study where the uncertainty of the GCM is amplified by the use of a downscaling method. Even if a selection process is used to make use of phenological models that are well adapted with the intended use, the uncertainty brought by these models remains significant and cumulates with climatic projections ones. The use of old phenological observations at the V2 validation stage is also a factor in prediction inaccuracy in the present study. This means that particular care should be used in drawing conclusions from the results presented above. In addition, complementary tests should be conducted with a larger set of climatic scenarios as they are needed to confirm the frost injury risk trends suggested here. With this understanding of the limits related to this study, several observations can be made from its output.

The model selection process showed that some of the models tested did not comply with the requirements, based on the purpose of this study. Phenological models LT3 and CF that were adapted from published models show average to unsatisfactory performances at the different evaluation steps. This leads to the conclusion that these adaptations are not successful. Even if the DD model does not produce unrealistic values under the climate change scenario, its accuracy is not up to the level of the LT's. Furthermore, the DD model reacts strongly to change in climate scenarios than LT5 and LT6 do. This would confirm Hanninen (1994) observations on the non light triggered models susceptibility to changes in climatic scenarios. LT5 and LT6 are the best performing models under the test conditions. LT6 shows slightly better performance at the V1 stage while LT5 appears as the most reliable model at the V2 stage. Based on these observations, the two models could be recommended for climate change impact studies. LT6 being based on a published model, it presents the interest of having been tested in different research situations. LT5, a model specifically designed and developed for this study, exhibits a high potential under climate change conditions and has the advantage of being based on less parameters than LT6. The latest can be an advantage for utilisation in conditions affected by a lack of long observation time series, which is needed for model calibration purposes.

The trend in risk of buds damage for apple trees in Québec due to spring frost under tested conditions shows an apparent increase. If confirmed through the use of the tools selected above under a representative number of climatic scenarios, the result would suggest that either a larger number of damaging frost events, their intensity, or both should increase in the future. Representative climatic scenarios could be obtained by using different CGM outputs, different emission scenarios and possibly other downscaling techniques. In addition, the applicability of such conclusions to a large number of different fruit production hypotheses would need to be verified through further tests on different crops prior to being accepted.

The increase in damaging frost occurrence prediction can possibly be explained by the characteristic of the climate change projections. As shown in Figure 5, the yearly average predicted temperature increase is not evenly distributed among the months. For instance, the month of January and February are predicted to be more affected by the temperature increase than April or May. In January-February, the apple trees ontogenetic development process is ongoing. A temperature increase in these months would therefore speed up the bud development process. If the temperature in April and May, the most critical months for the spring frost injuries, does not increase as fast as in January or February, spring low temperatures would affect buds developed to more temperature sensitive stages.

CONCLUSION

In the context of rising concerns of potential negative impacts of climate change on water resources, water demand management is of strategic importance. The utilisation of sprinkler irrigation as a frost protection method, due to the quantity of water required for an efficient protection, represents a risk of increase in overall crop water use for irrigation that needs to be further evaluated. The present study, by showing that climate change may increase the need for more protection against frost, suggests that more attention should be given to sprinkler irrigation frost protection practices. It also suggests that further studies should be conducted in order to validate the present findings, by using the phenological and Tcrit models under a large number of climatic scenarios.

The methodology that is used for trend analysis integrates two new models that have demonstrated their usefulness in the present conditions. Tcrit and its related spring frost injury risk index produces simple and efficient indicators of trends. Finally, the light-temperature triggered phenological model LT5 is the most suitable of the models tested in this study for apple tree phenological event predictions under climate change scenarios.

Acknowledgments

We thank the Climate Change Impacts and Adaptation Fund (CCIAF) for their financial support. Most of the phenological observations used in this study originate from the Québec Apple Network pilot orchards and were generously provided by Sylvie Bellerose from the IRDA (Research and Development Institute for the Agri-Environment).

Bano Mehdi and the Brace Center Working Group on Climate Change contributed through critical discussions and careful review of the manuscript. Rhami Aly Hassan and Pénéloppe Thériault played a large part in the models' calibration, validation and execution. Jeannie Shaddy proofread the document.

REFERENCES

Cesaraccio C., Spano D., Snyder R.L., Duce P., 2004: Chilling and forcing model to predict bud-burst of crop and forest species. Agricultural and Forest Meteorology 126, 1-13.

Charette R., Krueger R., 1992: The low-temperature hazard to the Québec orchard industry. Department of Geography publication series #32, University of Waterloo, 49-64.

Chuine I., 2000: A Unified Model for Budburst of Trees. Journal of Theoretical Biology. 207, 337-347.

Chuine I., Cour P., Rousseau D.D., 1999: Selecting models to predict the timing of flowering of temperate trees: implications for tree phenology modelling. Plant, Cell and Environment 22, 1-13.

Crepinsek Z., Kajfez-Bogatai L., 2006: Phenology an indicator of plant response to climate regime. Water Observation and Information System for Balkan Countries, website publication # FFP-556, 1-11.

Hanninen H., 1995: Effects of climatic change on trees from cool and temperate regions: an ecophysiological approach to modelling of budburst phenology. Canadian journal of Botany, 73, 183-199.

Jolivet Y., 2006: Mille et une recettes de lutte contre le gel printanier. Agri-vision conférence, Ministère de l'Agriculture des Pêches et de l'Alimentation du Québec, 25 Janvier 2006.

Koc A.B., Heinemann P.H., Crassweller R.H., Morrow C.T., 2000: Automated Cycled Sprinkler Irrigation System For Frost Protection of Apple Buds. Applied Engineering in Agriculture, 16 (3): 231-240.

Linkosalo T., Carter T.R., Hakkinen R., Hari P., 2000: Predicting spring phenology and frost damage risk of Betula spurs under climatic warming: a comparison of 2 models, Tree Physiology, 20: 1175-1182.

Picard G., Quegan S., Delbart N., Lomas M.R., Toan T., Woodward I., 2005: Bud-burst modelling in Siberia and its impact on quantifying the carbon budget. Global Change Biology 11: 2164-2176.

Pool B., Martinson T., Lerch S., Wilsey B., Chicoine D., 2004: The Perfect? Freeze. Talk at the Geneva grape field day, July 2004.

Reader M.A., Dracup M., Kirby E.J.M., 1995: Time to Flowering in Narrow-leafed Lupin. Australian Journal of Agricultural Resources, 46, 1063-1077.

Schwartz M.D., Reiter B.E., 2000: Changes in North America Spring. International Journal of climatology, 20**,** 929-932.

Snyder R. and De Melo-Abreu J.P., 2005: Frost Protectection: Fundamentals practice and economics. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Wees D., 2001: Hardy Fruit Handbook. McGill University publication, 45.

Wolfe D.W., Schwartz M.D., Lakso A.N., Otsuki Y., Pool R.M., Shaulis N.J., 2005: Climate change and shifts in spring phenology of three horticultural woody perennials in north-eastern USA. International Journal of Biometeorology, 49: 303-309.

Zinoni F., Antolini G., Brunetti A., Rossi F., Mariani L., Toller G.B., 2004: Cambiamenti climatici e Agrioltura. Progetto Climagri, Relazione Technica -2° anno di Attivita, published by the F.A.O.

REAL TIME WATER DELIVERY MANAGEMENT AND PLANNING IN IRRIGATION AND DRAINAGE NETWORKS

Vahid Karami[1]
Roghayeh Samadi Bahrami[2]
Ali Hosseinzadeh Dalir[3]

ABSTRACT

This paper focuses on delivery and demand management in irrigation and drainage networks as the largest water resource consumer. A model is developed for water demand management in irrigation networks. The model is capable of predicting actual water requirements in every field blocks and produces water delivery schedule for all network elements. In this model, planning water delivery schedule in irrigation network is accomplished by considering three important factors including crops irrigation calendars, water distribution method, and canals hydraulic conditions and performance. The model incorporates CANAL ROTATION & SEMI DEMAND method for water distribution in canals. Due to sizable quantity and spatial and temporal variations of required data and the necessity for updating the results in real time operation, all the required data are classified, stored and managed in a database system. The developed model is also capable of planning water delivery in canals upon sound simplifications of irrigation planning regarding proper water distribution criteria. In dry periods, the developed model compares actual required water with available water resources and modifies quantity and/or delivery time considering amount of available water. The model is incorporated in planning water delivery management system for RMC lot (4500 ha) in Irrigation and drainage Scheme (Aji-Chai) located in Tabriz plain, East Azerbaijan, Northwest of Iran.

INTRODUCTION

Nowadays, in most of developing countries the need for more productions together with scarcity of available water resources jeopardizes sustainable development in agricultural sector making it be facing with several numerous challenges. Due to lack of an accurate and proper management system in this sector, optimum usage of limited available water resources isn't achievable. The recent drought and decrease of rainfall and also over consumption have resulted in reduce available water resources. Irrigation and drainage systems are the greatest water consumer in the basins. Therefore, incorporation of optimum water use methods in these systems is essential. This would be achieved through revising the water resources allocations and incorporation of accurate delivery and demand management. In this paper, planning water delivery schedule in irrigation networks is investigated through considering three important factors: Crops irrigation calendar, water distribution method, and hydraulic conditions and performance of distribution canal. Results of these investigations have resulted in development of scheme-wise water delivery schedule model. The model determines the required amount and time of water delivery

[1] Expert of Mahab Ghodss Consulting Engineers Co.; 17 Takharestan St., Zafar St., Shariati St., Tehran, Iran; karami_v@mahabghodss.com
[2] Expert of ZEISTAB Consulting Engineers Co.; Tehran , Iran ; Samadi_R82@yahoo.com
[3] Professor of Faculty of Water Engineering, Tabriz University , Iran

to each farm plot for each irrigation turn. The model also compares scheme water requirement with available water resources and specifies the time & amount of water shortages during a cropping year. A case study has been conducted in Aji-Chai irrigation and drainage scheme located in Tabriz plain, in northwest of Iran to produce the water delivery schedule is RMC lot measuring 4500 ha.

METHODOLOGY

Water Delivery Management in Irrigation Networks

Water delivery management is conducted in irrigation schemes to supply farming plots water requirements based on proper water distribution criteria and methods to achieve a balance between deliveries and demands in the whole scheme. The main objective of in-scheme delivery management is timely distribution of adequate water to meet crop water requirements are more closer the gap between available water and actual requirements. Recognition of water resources and their potential yields as well as understanding the consumptions and demands are of high importance in irrigation scheduling & water distribution in irrigation networks. The irrigation management requires data on soils, climate, irrigation and drainage, canals layout, crops, land tenures, land uses and etc. Outputs of management activities include wide varieties of issues regarding water delivery & distribution existing drainage management, repair and maintenance requirement & planning and etc.

The data of each irrigation and drainage network must be carefully collected, packed and entered the system since they constitute the basis of all required calculations. The data are categorized in four classes as follows:

a) Irrigation Network Layout and Specifications: All specifications and properties of different parts of a network including available water resources, main canal, secondary & tertiary canals, intake gates, area downstream of each intake and etc.
b) Cropping Pattern Water Requirement: including reference crop ET, Gross and net irrigation requirements.
c) Irrigation Planning: in most of irrigation networks, the areas under cultivation of different crops and amount of available water resources are managed carefully. Also, climatically condition and market needs role over the areas under cultivation. Therefore, the planning would be different in different years.
d) Water distribution schedule: operation of a water distribution network varies considerably due to changes in management factors, climatic conditions, water quantity and quality, conveyance and distribution structures and distribution methods. There are several different methods for water distribution scheduling, which are selected & applied based on available water resources and demands volume and time. In current study, Semi Demand & Canal Rotational method is selected as the proper water delivery & distribution scheduling method regarding the domination conditions in the case study area. In this method, the demands are announced by farmers to network manager. The network manager, then, announces the time, discharge and volume of deliveries to farms after modifying the demands based on actual water resources and network capacity. In this system, rotation is incorporated in both tertiary & secondary canals. Rotation method

varies along irrigation seasons and region by regain. Rotation duration is based on calculations and experimental knowledge of each region. The delivery discharges must match the intakes gates capacity. One of the advantages of this method is its applicability and practicability during high demands or during droughts periods. In cases where actual available water resources are less then actual water requirements, following policies would be incorporated:

- Cultivation of low demand and early mature crops
- Local return flow reuse
- Reduction of irrigation requirements through deficient irrigation and exclusion of crops with high water consumption
- Irrigation efficiency improvement through farmers training and undertake proper irrigation management.
- Balancing water shortage in network by adapting water allocation from each water resource. In other words, incorporation uses of surface & groundwater resources.

MODEL STRUCTURE

Irrigation Network Water Delivery Management Model consists of three different interrelated parts including database data entry & storage, water delivery scheduling and demand modification.

Database Data Entry & Storage

All required information and parameters are entered into the database in the form of fixed and variable parameters. The parameters include three groups of information:

- Data on available water resources including surface & groundwater resources in different months. Dialogue from of these data is shown in figure 1.

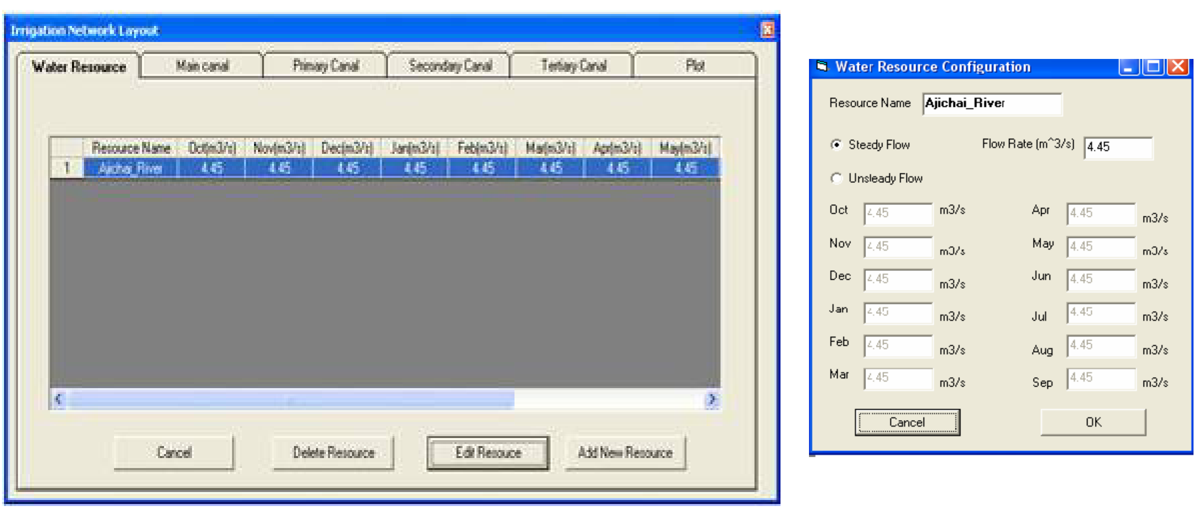


Figure1. Dialogue from of Water Resource Data

- Data on network layout, hydraulic characteristics of network parts, defined from upstream towards downstream as fixed parameters. Dialogue from of these data for tertiary canals definition with theirs hydraulic characteristics is shown in figure 2.

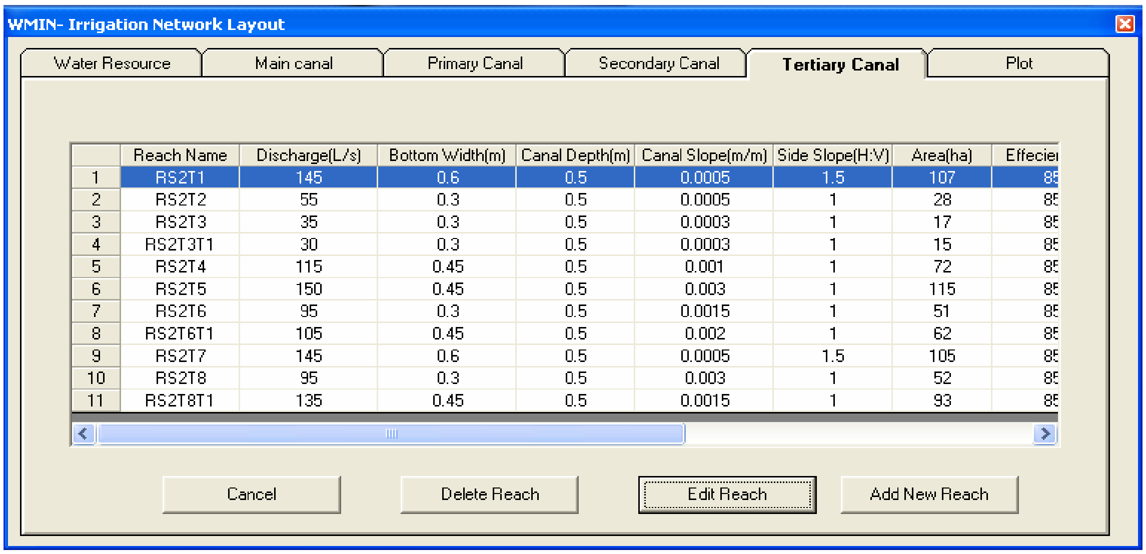


Figure2. Tertiary Canals Definition with Their Hydraulic Characteristics

- Data on cropping pattern and scheme water requirements. These data include cropping pattern, farming lots (area and crops cultivated in each lot), gross water requirements of all crops in cropping pattern, efficiencies, irrigation calendar and irrigation turns. Dialogue from of these data is shown in figure 3.

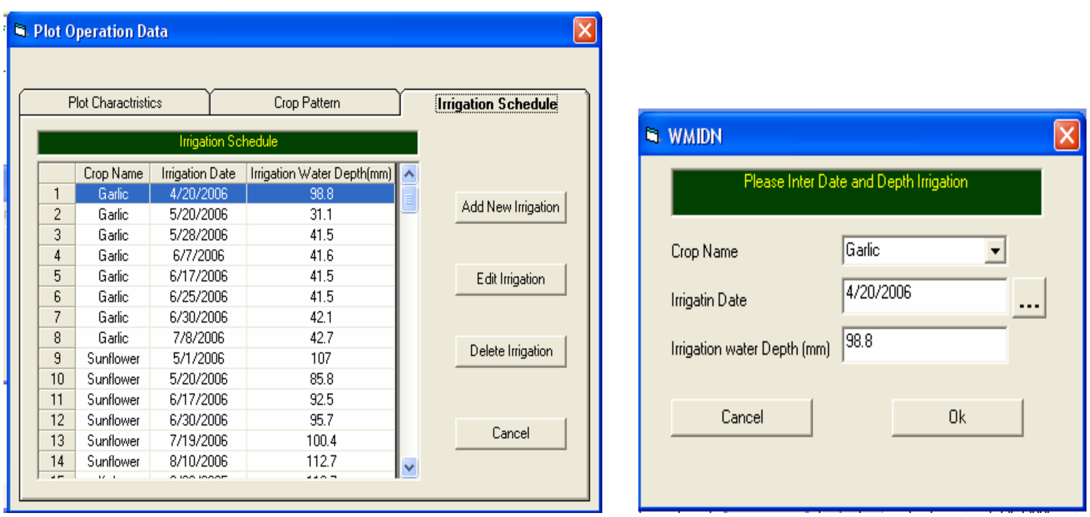


Figure 3. Irrigation Calendar of Crops in Cropping Pattern

In case of a highly variable cropping pattern, making use of irrigation schedule is either impossible or very difficult. In months with maximum requirement, often from June to august, all intakes must be operation on more than %70 of all days; this is impossible due to limitation in canals and structures design and water resources constraints. To resolve the problem same modifications and simplifications should be made on irrigation calendar. FAO has presented some levels of simplifications. To incorporate the methods one must consider actual cropping pattern to specify to what extent the designed cropping pattern is adhered to. In current study, irrigation calendar modification has been performed based on crop type, cropping calendar, crop susceptibility to water shortage in different development stages, yield reduction coefficient and etc.

Water Delivery Scheduling

Upon entry of all required data the model performs the calculations to determine irrigation intervals, the gate opening schedule and other needed parameters. To do so, the required volume of water at each farming plot is calculated based on and time and depth of irrigation for each crop cropping pattern. Considering hydraulic properties of intake all discharges passing through intake gates are calculated and, hence after, the gates opening time and delivered volume of water is determined. Number of gates that can be functioning at a same time may be determined based on tertiary canals hydraulic properties and water rotation program among the gates. The number of opened gates should be such that their total discharge does not exceed the canal discharge and the constraints on minimum velocity and Froude number are observed and fulfilled. Henceforth, the minimum and maximum number of tertiary intakes that can be functioning in each irrigation turn is specified. In this regard, to have a better management on water distribution among canals, their intakes are operated from downstream to upstream. These calculations are preformed in entire network for a cropping season and all irrigation turns resulting in determination of required water to be supplied and delivered to the scheme.

Water Demand Modification

To make the available water resource sufficient modification of water demands is considered. The model modifies the water demand based on available water resources. During pick demands or drought periods water demands do not correspond to available water resources. In such cases the model informs user on amount of deficiency and the difference between available and required water. Therefore the user can reduce the water demands to available water resources by incorporating different methodologies such as deficit irrigation, reduction of area under cultivation of high demand crops and etc.

Model Outputs

Main model outputs include irrigation parameters for farming plots separately farming units consumed water daring specified periods, gates opening and closing times, canal discharges and different water resources withdrawals. The model can also produce data required for crisis management such as delivery and demand management in low flow seasons or cropping pattern control. The model produces all required data in table formats.

Flowchart of calculation procedure is shown in Figure 4.

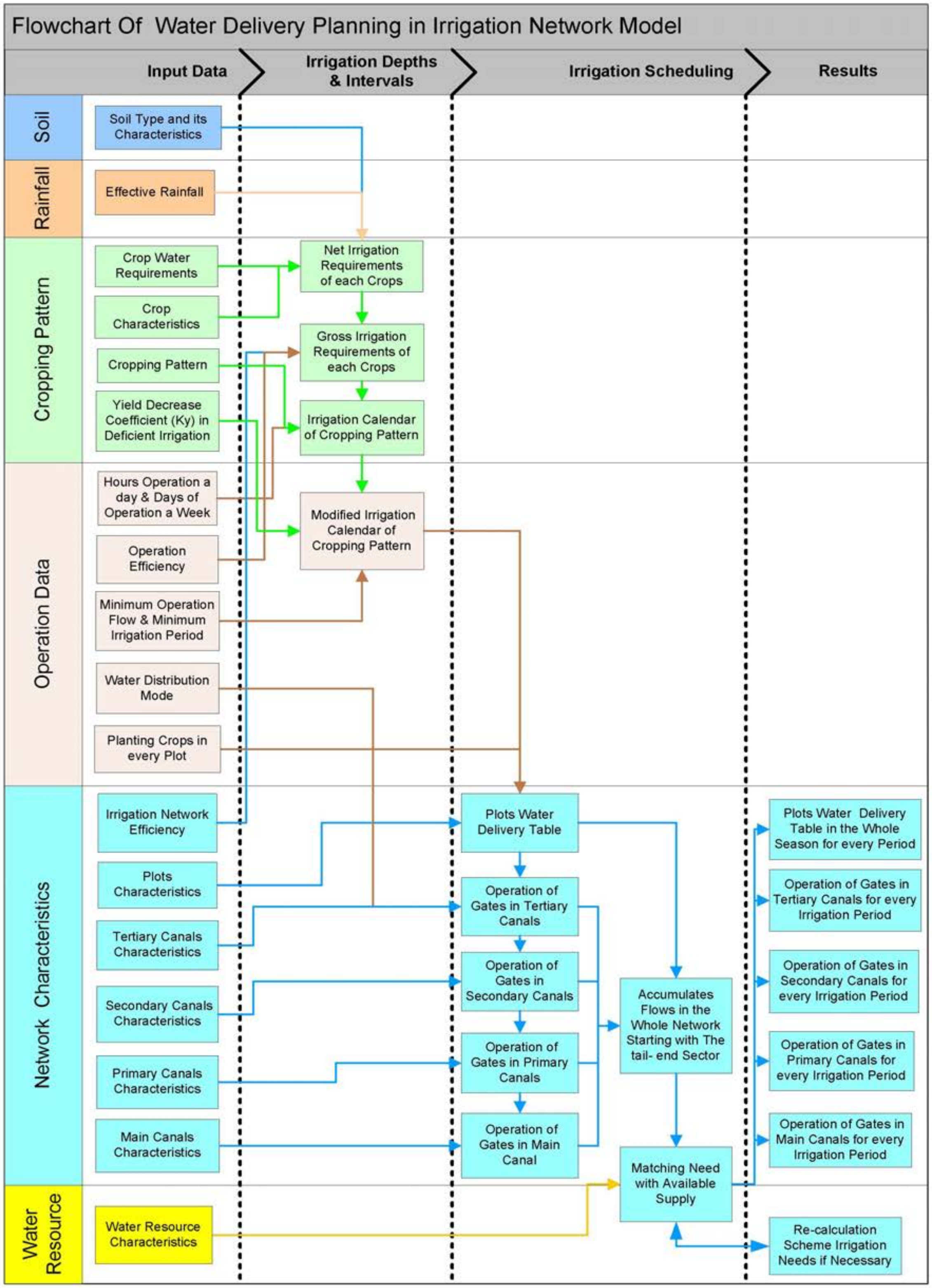


Figure 4. Flowchart of Water Delivery Planning for Irrigation Scheme

CASE STUDY

A part of Tabriz Plain Irrigation Scheme is used to test the model capabilities. The scheme is located on left bank of SENIKH CHAI with a gross area of 25000 ha subdivided into LMC, AMC and RMC lots. In current study, the model is applied on RMC lot measuring 5000 ha gross. The plan of studied irrigation network is shown in figure (5).

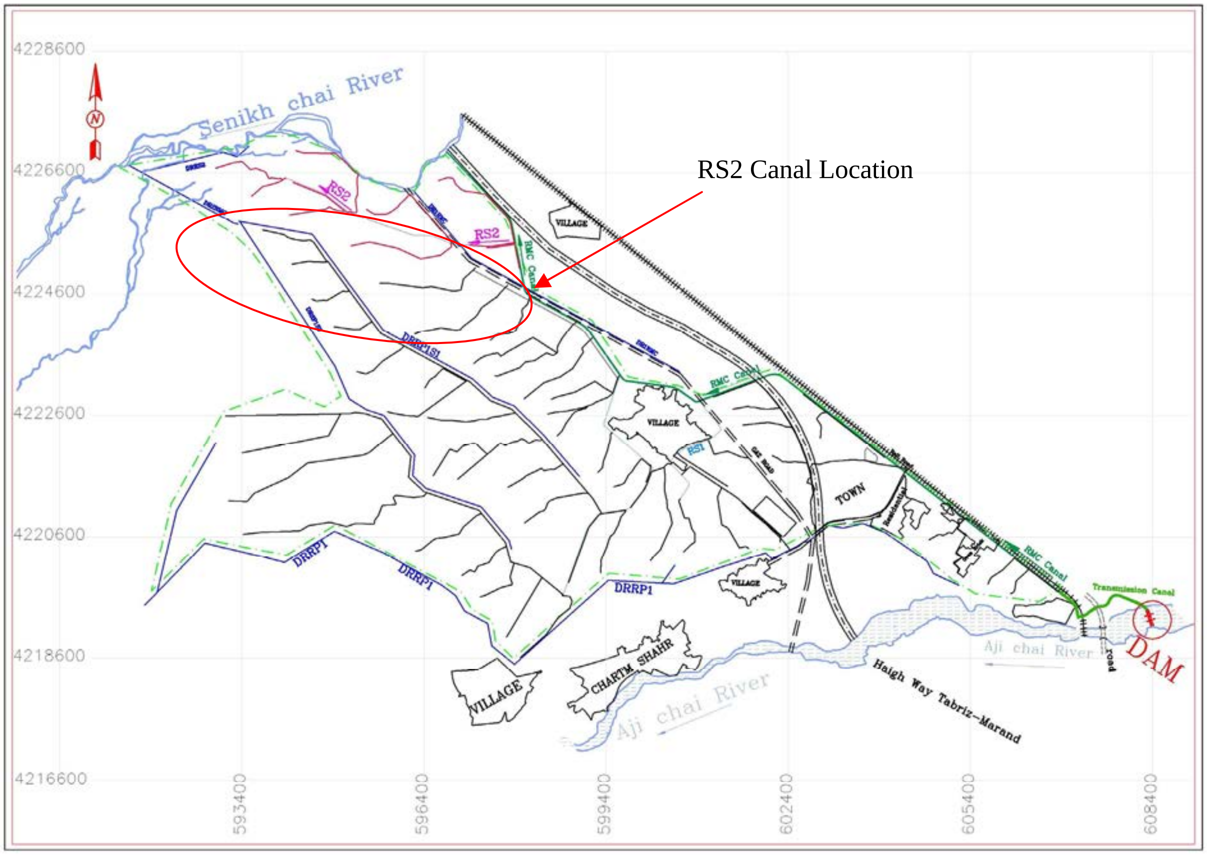


Figure 5. Plan of RMC Lot of Tabriz Plain Irrigation Network.

All of physical and hydraulic characteristics of irrigation network components such as cropping pattern, irrigation calendar, area of crops in each farming lot and the characteristics of all canals are stored in a data bank. The model always has access to the data bank. The model retrieves the data from the data bank and stores the results of all calculations in related tables in the data bank.

Adjustment Tabriz Plain Irrigation Calendar

Because of diversity in crops included in cropping pattern (17 crops) in Tabriz plain irrigation scheme and irregular irrigation dates during the cropping season, especially in high demanding months, using this irrigation calendar in this irrigation scheme is not possible. As an assumption considering cropping pattern in each farm and using this irrigation calendar will result in 18 days of operating canals and intake gates in July. On the other hand, respecting tertiary canals capacity and the allowable flow velocity in the farm canal, in some days of peak demanding months, the gate of intake must be kept open more than 24 hours. This will result in overlapping of irrigating turns and periods. During irrigation period with low water requirement the problem of flow velocity Re-reduction and sedimentation in canals arises. Therefore, the irrigation calendar has been modified and adjusted based on crops susceptibility to water deficit during its different growth stages (referenced to FAO publication no.33). To do so, the objective was to achieve minimum yield reduction due to changes in irrigation dates considering the most susceptible crop growth stage (table1). In this process, the constraints observed included canal hydraulic specifications, minimum and maximum allowable gates discharges and a maximum 24 hours opening time for each gate during each irrigation turn. The irrigation calendars for June and July, before and after modifications and adjustments, are presented in table 2 and 3, respectively.

Table 1. Yield Reduction Coefficients in Tabriz Plain Cropping Pattern at Difference Growth Stages

NO.	CROP_NAME	Initial	Development	Mid	Late	Total
1	Garlic	0.4	1.1	0.8	0.4	1.05
2	Sunflower	0.4	0.6	0.8	0.8	0.95
3	Kolza	0.2	0.8	1	0.3	0.85
4	Cumin	0.2	0.8	1	0.3	0.85
5	Onion	0.45	0.6	0.8	0.3	1.1
6	Orchards	0.4	0.6	0.8	0.8	0.8
7	Grape	0.2	0.7	0.85	0.4	0.85
8	Cow-Pea	0.2	0.7	0.85	0.4	0.85
9	Wheat	0.2	0.6	0.5	0.4	0.6
10	Pea	0.2	0.7	0.85	0.4	0.85
11	Alfalfa	1	1	1	1	1
12	Potato	0.45	0.8	0.8	0.3	1.1
13	Barley	0.2	0.6	0.5	0.4	1
14	Safflower	0.3	0.55	0.6	0.2	0.8
15	Sorghum	0.2	0.55	0.45	0.2	0.9
16	Sugerbeet	0.5	0.8	1.2	1	1
17	Vegetables	0.8	0.4	1.2	1	1

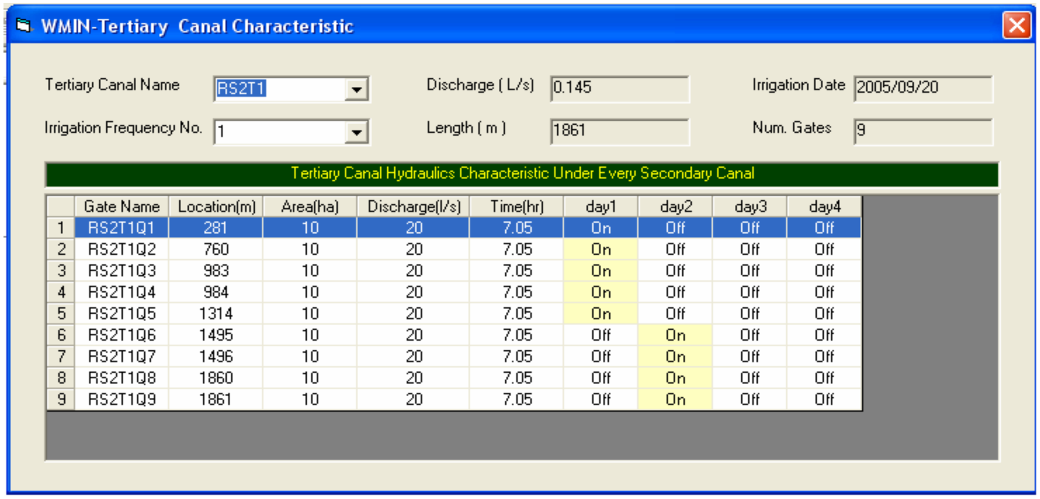
Table 2. Cropping Pattern Irrigation Calendar Base on Calculated Water Requirement in Peak Months (mm) (Before Adjustment)

No	Crop Name	June																	July																	
		1	2	5	7	8	9	10	13	16	17	20	21	22	25	26	29	30	1	3	8	10	11	13	15	16	17	19	20	22	23	24	27	28	30	31
1	Garlic				42						42					42				42			43													
2	Sunflower									93								96											100							
3	Kolza											67																								
4	Cumin											56																								
5	Onion					37					37				37				37		38				40					41				35		
6	Orchards	80															82															85				
7	Grape	65																	80																	82
8	Cow-Pea	28																31			39					44					42				45	
9	Wheat		72											83																						
10	Pea			58									60						61				59													
11	Alfalfa				71													84									85									
12	Potato						32						38					44			42					44						45				
13	Barley							91																												
14	Safflower								91																											
15	Sorghum																125											123								
16	Sugerbeet									66								81						85									89			
17	Vegetables										29							37			45	40						45					45			

Table 3. Adjustment Irrigation Calendar of Tabriz Plain in Peak Months (mm)

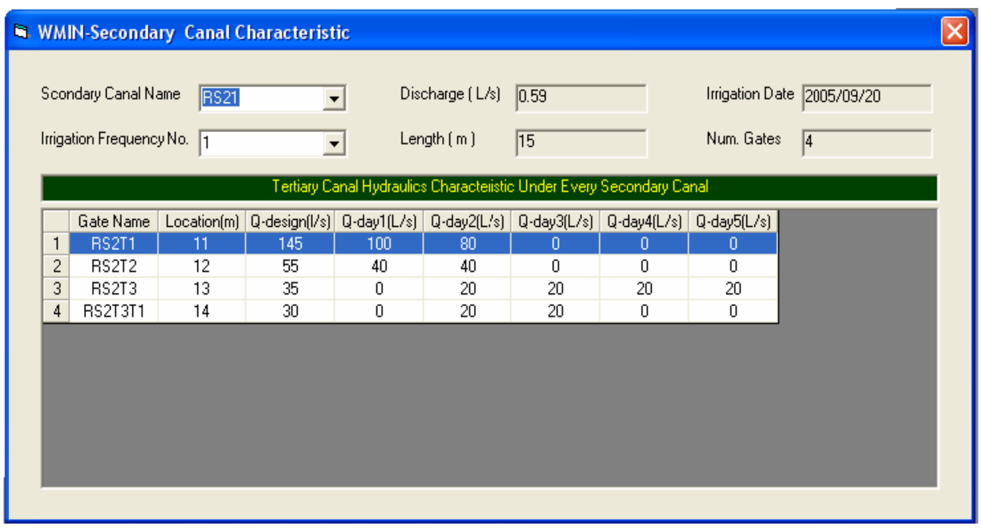
No	Crop Name	June								July						
		1	5	9	13	17	21	25	30	7	12	16	20	23	27	31
1	Garlic		42			42		42	42		43					
2	Sunflower					93			96				100			
3	Kolza						67									
4	Cumin						56									
5	Onion	36		37		37		37	37	38		40		41	35	
6	Orchards	80							82					85		
7	Grape	65							80							82
8	Cow-Pea	28							31	39		44		42		45
9	Wheat	72					83									
10	Pea		58				60		61		59					
11	Alfalfa		71						84			85				
12	Potato			32			38		44	42		44		45		45
13	Barley			91												
14	Safflower				91											
15	Sorghum							125					123			
16	Sugerbeet					66			81		85				89	
17	Vegetables					29			37	40			45		45	

The samples of irrigation schedule in RS2 canal located in Tabriz Plain RMC lot are shown in figures 6and 7.



	Gate Name	Location(m)	Area(ha)	Discharge(l/s)	Time(hr)	day1	day2	day3	day4
1	RS2T1Q1	281	10	20	7.05	On	Off	Off	Off
2	RS2T1Q2	760	10	20	7.05	On	Off	Off	Off
3	RS2T1Q3	983	10	20	7.05	On	Off	Off	Off
4	RS2T1Q4	984	10	20	7.05	On	Off	Off	Off
5	RS2T1Q5	1314	10	20	7.05	On	Off	Off	Off
6	RS2T1Q6	1495	10	20	7.05	Off	On	Off	Off
7	RS2T1Q7	1496	10	20	7.05	Off	On	Off	Off
8	RS2T1Q8	1860	10	20	7.05	Off	On	Off	Off
9	RS2T1Q9	1861	10	20	7.05	Off	On	Off	Off

Figure 6. The Gate Opening Schedule Table in RS2T1 Tertiary Canal
in the First Irrigation Turn



	Gate Name	Location(m)	Q-design(l/s)	Q-day1(L/s)	Q-day2(L/s)	Q-day3(L/s)	Q-day4(L/s)	Q-day5(L/s)
1	RS2T1	11	145	100	80	0	0	0
2	RS2T2	12	55	40	40	0	0	0
3	RS2T3	13	35	0	20	20	20	20
4	RS2T3T1	14	30	0	20	20	0	0

Figure 7. Water Delivery Table to Tertiary Canals of RS21 Canal
in the First Irrigation Turn

CONCLUSIONS

Real time management of irrigation and drainage scheme are not possible except using computer models. As shown, the developed model is capable to provide the irrigation calendar based on cropping pattern, characteristics of irrigation network and accessible water resources. In other words, the water distribution program for the next year upon selling of water to farmers in the beginning of the cropping year, respecting to type and area under cultivation of crops, and considering the accessible water resources will be setup. This program contains the duration, discharge and volume of deliverable water to each farming lot.

Water delivery program to tertiary canals including discharge, time, hydraulic properties, and intake gates opening-closing order based on their capacity is developed based on program of water delivery to farming lots. Water delivery programs for all upstream canals including secondary, primary and main canals are developed as well. Therefore the scheme water requirement is determined for each irrigation turn. Upon comparing the requirement and allocated water, deficit or surplus of resources is determined. In case of water deficit, the scheme manager can modify the demand-delivery relationship by taking appropriate measures. These measures include adjustment of cropping pattern and reducing area under cultivation of high demand crops, incorporating deficit irrigation, reduction of total area under cultivation, and incorporation of water reuse techniques.

ACKNOWLEDGEMENT

Authors hereby express their gratitude to Yekom Consulting Engineers especially Mr. Shantia, managing director, for his kind cooperation in smoothing the progress of this study. The authors also acknowledge Mr. Daneshvar for his dedication and time he made for his valuable consultation.

REFERENCES

Fipps, G. and Leigh, E. 2000. GIS- Based management system for irrigation districts. Proceedings of International Conference on Challenges Facing Irrigation and Drainage in the New Millennium, USCID, Fort Collins, U.S.A., June 20-24, pp. 103-116.

Huang, Y. 2003. Modeling Flows in Irrigation Distribution Networks Model Description and Prototype.Biological and Agricultural Engineering Department, Texas A$M University. Written for presentation at the 2003 ASAE; Las Vegas, Nevada, USA, 27-30 July

Mladen, Todorovic, Pasquale and Steduto .2002, A GIS for irrigation management.

Rao, N.H., Sheena M. and Sarma P.B.S. 2004. GIS Based Decision Support System for Real Time Water Demand Estimation in Canal Irrigation System "; CURRENT SCIENCE, Vol. 87, No.5

Ronoff, S.1991. Geographic information systems: A Management Perspective. WDL Publications, Ottawa.

Sagardoy, J.A., Bottrall, A. and Uttenbogaard, G.O.1986. Organization Operation and Maintenance of Irrigation Schemes, FAO. Paper 40.

Samadi. bahrami.R 2006, Application of Geographic Information System (GIS) in Operation & Management of Irrigation & Drainage Networks, water engineering department Tabriz University

Sarangi, a., Rao , N.H. , Brownee, S.M. and Singh, A.K.2001. Use of Geographic Information System (GIS) tool in watershed hydrology and Irrigation Water Management. New Delhi. pp .1- 4.

Vanden Bulcke, M., Sagardoy, J.A. , Hatcho,N. , Bellostas, J.M.1996. User Manual of SIMIS (Scheme Irrigation Management Information System). FAO.

GROWTH RESPONSE OF PALM TRESS TO THE FREQUENCY OF IRRIGATION BY BUBBLERS IN KHUZESTAN, IRAN

H.A. Kashkuli[1]
K. Khodadadi[2]
H. Siadat[3]
M. Vaeli Zade[4]

ABSTRACT

Based on the shortage of water resources in Iran and the high evapotranspiration rate in Khuzestan region (2044 mm/year), an irrigation system on Estamaran palm tree in the Experimental Farm of Shahid Rajaee of Omidiyeh plain was conducted.

This study had two purposes, namely irrigation frequency and suitable depth of irrigation application of the Estamaran palm trees in Omidiyeh region. This study had two objectives. Irrigation frequency was the primary treatment and the evapotranspiration estimating methods was the secondary treatment. Three irrigation levels. i.e. one day long (A1), two day long (A2) and three day long (A3), were used as irrigation frequency. Also the evapotranspiration estimating methods used were, Penman-Montith 100% (B1), Penman- Montith 70% (B2), class A pan 100% (B3) and class A pan 70% (B4). Since this study had three replications, 36 palm trees were selected for this experiment. Cropwat software V.4 for windows, was applied for the evapotranspiration estimating from Penman-Montieth method. Irrigation scheduling was done according to SCS recommendations. Experimental design was according to split plot method in a randomized block. Finally by measuring the different growth indices of palm trees (leaf number, barb number and leaflet length) at a definite time, the best treatment was determined. The results showed that as a whole all the treatments in this experiment did not show a significant difference (up to 5% level) for the indicated indices. However, at the end of 4 month since the beginning of this study, the growth indices of trees in A2B1, A1B2 and A1B1 increased compared to other treatments. The result also indicated that, A1B2 was the best treatment of all. In comparison with the traditional irrigation by local farmers, using A1B2 treatment for all the palm trees (from Aug to Nov), will have 28422.34 m^3 water saving in 3.87 hectare per month.

INTRODUCTION

Yearly total rainfall received on the surface in Iran is about 400 billion, cubic meters (BCM), out of which 280 BCM is lost through evapotranspiration and the remaining 120 BCM is either surface runoff or infiltrates to raise soil moisture or join groundwater. A third of the total surface water of the country (about 34 BCM) flows through rivers passing the vast Khuzestan plain (3,6). However the total cultivable land area of Khuzestan exceeds 1.6 million ha,. out of which,

[1] Professor, University Research Center , Ahwaz, Iran
[2] Graduate student , Ahwaz University Research Center, Ahwaz , Iran
[3] Research Professor Soil and Water Research Institute ,Tehran, Iran
[4] Field Research Assistant , Sharab Consulting Engineers, Ahwaz,Iran

540,000 ha is under irrigation. Total area under modern irrigation in Khuzestan is at present 238,320 ha. and is planned to finally reach 800 thousand hectars, under modern irrigation projects (1,8,12)

The Soil and Climate of Khuzestan is suitable for diverse agronomic and horticultural farming throughout the year and produces about 14 percent of the total agricultural production of the country (12). One of the major crops in this province is date palm. Although this crop is adapted to dry conditions, higher yields can be obtained with irrigation. With about 30 million palm trees covering a total area of 216 thousand hectares, the total date production in Iran is about 900 thousand tons. In spite of the importance of this crop, so far little is known about the potential of raising yield for this crop through modern irrigation research (9).To determine the proper irrigation depth and interval for Estamaran date palm trees grown on Omidieh experimental field, this field research experiment was designed.

MATERIALS AND METHODS

This research started on February 20, 2005 and continued unit the end of November 2006. The experimental site is a 50 hectare field in Omidieh, located south east of Khuzestan, 180 KM from the central city of Ahwaz. The mean annual rainfall in Omidieh is about 266 mm. The experiment was designed as split plot based on complete randomied blocks (CRB) with 12 treatments and 3 replications (total number of 36 trees). The main variable factor was irrigation frequency taken at 3 levels; daily (A1) , two day (A2) and three day (A3) intervals. The secondary variable factor was the method of estimation of the depth of irrigation applications based on Penman -Montieth (100%) (B1), Penman-Montieth (70%) (B2) Class A pan 100% (B3) and class A pan 70% (B4).

Irrigation water is carried through a 90 mm submain, feeding a number of 32mm manifolds. Laterals take water from these manifolds and delivers water to the bubblers beside palm trees grown at a spacing of 8m×8m. A round basin is dug around every tree about 1.5m in diameter .The soil of the experimental site was a sandy loam with a PH of about 8 and ECe of 1.8 ds/m. Final intake rate of soil was 6-8 mm/h which improved by the addition of organic matter to basins. EC of irrigation water was measured to be 2.71, 2.75, 2.86 and 2.91 ds/m for the end of July, August, September and October.

- Preparations before starting irrigation included:
- Separating the selected trees
- Separating female pods for pollination
- Weeding
- Pruning and cutting
- Manuring with fertilizer application
- Marking and tagging leaflets and thorns for growth measurement.
- Calibration of bubblers for a fixed discharge of 222 liters / hour with an inlet pressure of 2.5 bars.

Irrigation water requirement of palm trees was calculated using climatological data of the period 2000-2004 and potential evapotranspiration of reference crop ETo, estimated with pan evaporation record according to the following :

ETo = Kp Epan

Kp = pan Coefficient
Epan = pan evaporation mm/day

Kp= 0.475 – 0.24 *10-3 (U2m)+0.00516 (RHmeam)+0.00118(d)-0.16×10-4 (RHmean)2
-0.101×10-5(d)2 – 0.8 ×10-8 (RH mean)2(U2m) - 1×10-8(RHmean)d
-1×10-8(RH mean)2 d

Where

U2m = wind speed at 2m height (Km)
RH mean = mean relative humidity %
d = Green fetch area m

ETo was also estimated by Penman Montieth method, using computer software (Cropwat 4, Ver. 4.2) (10). A crop coefficient (Kc) of 0.9 was used for date palm . Effective rainfall was estimated using 80% probable mean monthly rainfall.

$$Pe = [1.252496 \times p_m^{0.82416} - 2.93522] \times 10^{(0.00095512 \times ETc)}$$

Pe = effective rainfall (mm/month)
Pm = mean rainfall mm/month
ETc = potential evapotranspiration

We also have :

Pe (80%)= pe * 0.66

Considering that in drip irrigation soil surface evaporation losses are minimal and almost all the water consumed is lost by transpiration, calculation of mean daily transpiration of date palm is given by

Td = Ud [Ps/100 + 0.15 (1-ps/100)]

Td=mean maximum daily transpiration (Corrected with 80% effective rainfall)

Ud=mean maximum daily consumptive use
Ps=percent plant cover
(Table 1.)

Net depth of irrigation application (In) is derived as:

In = T * Fi
(Table 2.)
Mean maximum irrigation requirement (Ig) is estimated by

Ig = (In* Tr) / (Ea/100)

Tr = Transpiration ratio during peak period
Ea = Irrigation Efficiency or

Ea= Eu × Et

Eu= Uniformity of dripping
Et = Crop water use efficiency

Table 1. shows that during November-December and December-January, 80% probable monthly effective rainfall exceeds mean maximum monthly transpiration for date palm , therefore there was no irrigation application for this period. It was assumed that due to resistance to moisture stress, date palm trees can overcome the nonuniformity of rainfall without reduction in growth.

Table 1. Water requirement of treatments from July to January

month	ETc & Td (mm/day) and Pe80% (mm/month)											
	Penman-Montith 100%			Penman-Montith 70%			Class A Pan 100%			Class A Pan 70%		
	ETC	Td	Pe80%	ETC	Td	Pe80%	ETC	Td	Pe80%	ETC	Td	Pe80%
J-A	16.23	3.5	-	11.36	2.45	-	6.72	1.45	-	4.71	1.01	-
A-S	15.05	3.24	-	10.53	2.27	-	5.19	1.12	-	3.64	0.78	-
S-O	11.38	2.45	-	7.96	1.71	-	4.23	0.91	-	2.96	0.64	-
O-N	8.3	1.79	8.5	5.8	1.25	7.21	2.43	0.52	5.8	1.7	0.37	5.5
N-D	3.98	0.86	38.07	2.79	0.6	35.19	1.32	0.28	31.94	0.93	0.2	31.13
D-J	2.9	0.62	36	2.02	0.43	33.96	1.03	0.22	31.81	0.72	0.15	31.17

Table 2. Net depth of irrigation for all the treatments

A3B4	A3B3	A3B2	A3B1	A2B4	A2B3	A2B2	A2B1	A1B4	A1B3	A1B2	A1B1	Treatments
3.03	4.35	7.35	10.5	2.02	2.9	4.9	7	1.01	1.45	2.45	3.5	July-Aug
2.34	3.36	6.81	9.72	1.56	2.24	4.54	6.48	0.78	1.12	2.27	3.24	Aug- Sep
1.92	2.73	5.13	7.35	1.28	1.82	3.42	4.9	0.64	0.91	1.71	2.45	Sep-Oct
0.57	0.99	3.03	4.53	0.38	0.66	2.02	3.02	0.19	0.33	1.01	1.51	Oct-Nov

Gross daily requirement of a crop in liters per day is estimated by the following equation:

G=(Ig/Fi) × Sp × Sr
Where

Sp = distance between trees in each row
Sr = distance between rows of trees
(Table 3.)

Table 3. Gross depth of irrigation from July to November (mm)

month	A1B1	A1B2	A1B3	A1B4	A2B1	A2B2	A2B3	A2B4	A3B1	A3B2	A3B3	A3B4
J-A	4.47	3.13	1.853	1.29	8.94	6.26	3.71	2.58	13.42	9.39	5.56	3.87
A- S	4.14	2.9	1.43	1	8.28	5.8	2.86	1.99	12.42	8.7	4.29	2.99
S-O	3.13	2.18	1.16	0.82	6.26	4.37	2.33	1.64	9.39	6.55	3.49	2.45
O-N	1.93	1.29	0.42	0.243	3.86	2.58	0.84	0.49	5.79	3.87	1.26	0.73

Time of water application, Ta, in hours is calculated with the following equation:

$$Ta = G/ (Np \times qa) \times Fi$$

Where

Np = number of drippers surrounding a tree
qa = drippers discharge l/h

RESULTS AND DISCUSSION

Daily gross water requirement for all the treatments is given in Table 4.

Table 4: Daily gross water requirement for all treatments

Treatments	Lit/day , G			
	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov
$A_{1,2,3}B1$	286	265	200	124
$A_{1,2,3}$ B2	200	186	140	83
$A_{1,2,3}$ B3	119	92	74	27
$A_{1,2,3}$ B4	83	64	52	16

The record keeping activity started on July 23 and the last measurement took place on November 22. As seen from the table of measured characteristics from each treatment, no changes were observed until Oct 23 and only slight changes were noted on November 22. Analysis of data collected from all the treatments was performed with Spss 13. for Windows and the table of analysis of variance for each crop characteristics in each treatment was constructed.

According to the results of the analysis of variance for all the variations in crop characteristics including number of leaves, thorns, length of leaf in the 4 month period of experiment, did not show to be significant at 5% level. This was due to drought resistance of palm tree and its slow growth rate, which masks the appearance of growth indicators during this short period. Besides the above discussion about the significance of growth characteristic indices, as seen from the tables of measured characteristics of different treatments during the fourth month of this experiment, growth factors in the treatment A1 B1, A1B2 and A2 B1 , were more comparable to other treatments. Among those treatments A1B2 (Penman - Montieth 70% and daily irrigation) was the most appropriate treatment.

Selection of this treatment to be the most appropriate treatment compared to A2B1 and A1B1, is due to the fact that with the same amount of growth, the above treatment had received less water. Therefore it can be concluded that this treatment can lead to a better water use efficiency of date palm in Omidieh. Recommendation of (A1B2) treatment as the most appropriate for date palm growers will result in a saving of about 28422.34 m3 in 3.87 hectare per month compared to routine practices in the area (Table 5). Total number of date palm trees in the whole field was 610 and bubblers with a bubbler discharge of about 750 liters/hr and irrigation application interval of 2 days in July – August and 3 days in October-November was performed. In a series of research conducted by the Work Group of Agricultural Products of Iran (WGAPI), Penman - Montieth method was compared with FAO24, Corrected Penman, Radiation and Blany Criddle method, for many weather stations (9).

Table 5: Comparison of the water requirement of A1B2 treatment with routine irrigation practice for the same area of 3.87 hectare

Irrigation frequency and depth	Total water volume cubic meters for 3.87 hectares			
	July-Aug	Aug-Sep	Sep-Oct	Oct-Nov
A1B2 treatment	3782	3517.26	2562	1518.9
Routine irrigation practice (frequency & depth that is presently performed on the farm)	14182.5	14182.5	6862.5	4575

Penman - Montieth was selected as the most appropriate method and gave the lowest ET0. Therefore we conclude that ETo by pan evaporation method can be used more advantageously in Omidieh which is a dry region. It can be concluded that for Estamaran date palm in Omideh region, if enough water is available treatment (A1B2) is recommended. Otherwise with less water available treatments using pan evaporation are more appropicate.

Table 6: Comparison of reference potential evapotranspiration by Penman-Montith and Class A Pan in Omidiyeh

Method of estimation	Reference crop potential evapotranspiration mm/day					
	July-Aug	Aug-sep	Sep-Oct	Oct- Nov	Nov-Dec	Dec-Jan
Penman Montith	18.03	16.72	12.64	9.21	4.42	3.21
Class A Pan	7.47	5.77	4.7	2.7	1.47	1.14

REFERENCES

1. Arshad, K. 1997. Evaluation of the depth and frequency of drip irrigation for date palm, Shabankareh date palm research station annual report.

2. Arshad, K. Moradi, 6. and Kaviani, A, 1998. Evaluation of water requirement, irrigation depth and frequency for Dashtestan date palm, Bushehr Soil and water research station annual report, Bushehr, Iran.

3. KWPA. 2001. Water Balance and Conjunctive use department , water balance and consumptive studies of rivers in Khuzestan province, annual report, Ahwaz, Iran.

4. Alizadeh, A. 2001. Irrigation system design by Cuenca, persian translation, Razavai publishing company, Meshhad, Iran.

5. Daneshnia, E. and Rastegar, H., 1999. Determination of the most suitable irrigation frequency and depth, in drip irrigation for Shahani date palm, final research report, Jahrom research center, Shiraz, Iran.

6. IRNCID 2003. Proceedings of the 11th Irrigation and Drainage National Conference, Tehran, Iran.

7. FAO 1978. Effective rainal, Irrigation and Drainage Paper No 25, Rome, Italy.

8. Ghaffarinezhad, E. and Ehsani, A. 2001. Determination of a suitable irrigation depth and frequency for Mazafali date palm, fnal research report, Bam-Jiroft Agriculture Research Center, Bam, Kerman, Iran.

9. Mohebbi, E. 2002. Evaluation of irrigation system and water requirement of Pirom date palm, final research report, date palm and tropical fruit research institute of Iran, Ahwaz, Iran, PP48.

10. Sahaf. A. B. and Farshi, E. 1999. Drip irrigation fundamentals, Irrigation Network Design, Ministry of Higher Education, Nashr. Press, Tehran, Iran.

11. Tamab, 1996. Bulletin of the water resources of Iran, Ministry of Power, Iran.

12. IRNCID. 2002. Evaluation and Comparision of evapotransplration estimation methods, WGSWU, report Tehran, Iran.

13. Zia-Tabar, M. 1992. U.S. Soil Conservation Service, National Engineering Handbook, Section 7, Part 15.Persian translation Mazandaran University Press, Iran.

APPLICATION OF BACKPROPAGATION NEURAL NETWORK TO ESTIMATE EVAPOTRANSPIRATION FOR CHIANAN IRRIGATED AREA, TAIWAN

Sheng-Feng Kuo[1]
Ming-Hua Tsai [2]
Wei-Taw Lin [3]
Yi-Fong Ho [4]

ABSTRACT

Backpropagation Neural Network is applied to establish the relationship between meteorological factors and evapotranspiration, which is then used to predict the evapotranspiration in ChiaNan irrigated area, Taiwan. It takes the weather data from Irrigation Experiment Station of ChiaNan Irrigation Association as the input layer, which include the following weather factors: (1) the highest temperature; (2) the lowest temperature; (3) average temperature; (4) relative humidity; (5) wind speed; (6) sunlight hours; (7) solar radiation amount; (8) dew point; (9) forenoon ground temperature; (10) afternoon ground temperature.

From the result it can be known that the correlation coefficient reaches 0.993 between the evapotranspiration in 2004 calculated by FAO56 Penman–Monteith method and the one predicted by the neural network model with a hidden layer of 10 nodes. The actual evapotranspiration is 911.6cm and the prediction by the neural network is 864.4, between which the error ratio is 1.67%. The correlation coefficient is 0.708 between the actual evaporation in 2004 and the prediction by the neural network with a hidden layer of 10 nodes and an output layer with the pan evaporation as its target output. The pan evaporation is 1674.1cm, while the prediction by the neural network is 1451.7cm, between which the error ratio is 13.23%.

INTRODUCTION

Evapotranspiration refers to the amount of water needed for the normal growth of the crop and becomes the most basic data for the irrigation association to study out annual irrigation plan and estimate the water use amount for agriculture. According to the standard method recommended by Food and Agriculture Organization (FAO), the indirect estimate on the crop evapotranspiration can be divided into two steps: (1) to roughly estimate the potential evapotranspiration according to agricultural weather data and empirical formula; (2) to get the value of the evapotranspiration needed during the crop growth by multiplying the potential evapotranspiration by the crop factor of different crop during different growth phases.

---

[1]Professor, Dept. of Resource Environment, Leader University, Tainan 709, Taiwan. Member, Asian Regional Working Group, ICID; kuosf@mail.leader.edu.tw
[2] Director, Irrigation and Engineering Dept., Council of Agriculture, Taipei, Taiwan. Vice Chairman, Chinese Taipei Committee, ICID; mhtsai@ mail.coa.gov.tw
[3] Section Chief, Irrigation Management Sec., Council of Agriculture, Taipei, Taiwan. Deputy Secretary General, Chinese Taipei Committee, ICID; lwt@ mail.coa.gov.tw
[4] Specialist, Irrigation Management Sec., Council of Agriculture, Taiwan. Graduate Student, Dept. of Civil Engineering, National Taiwan University, Taipei, Taiwan; yifong@ mail.coa.gov.tw

In recent years, several articles on the estimate of crop evapotranspiration have been published. Irmak et al. (2003a) study the important topic of how to efficiently apply Florida agricultural water resource to solve the increasingly rising demand on water resource, and therefore, evaluate 21 types of formula, with grass and alfalfa as norm, to estimate the crop evapotranspiration for further agricultural water use management. Irmak et al. (2003b) also adopts the empirical formula with net radiation as base to estimate the potential evapotranspiration in humid area. As known from above, since 1940, lots of empirical formulas have been developed internationally to estimate the non-linear relationship between potential evapotranspiration and crop weather data. Current empirical formulas can be classified into four types: (1) Blaney- Criddle Method; (2) Radiation Method; (3) FAO56 Penman–Monteith Method; (4) Pan Evaporation Method. The agricultural weather data they need include: (1) the highest and lowest temperatures; (2) wind speed; (3) sunlight hours; (4) relative humidity; (5) rainfall; (6) solar radiation, etc.

In recent years, artificial neural network has been widely applied to understand the non-linear issue of water resource and agricultural management. Yang et al. (1997) applies ANN to simulate the non-linear relationship between the ground temperature 10^{cm}, 50^{cm} and 150^{cm} below and the agricultural weather, among which the used weather data include rainfall, potential evaporation, maximum and minimum temperature. Han & Felker (1997) adopts ANN to estimate relationship among evapotranspiration and relative humidity of surface oil, wind speed and soil moisture content, and then compares the results with multiple linear regressions. Burks et al. (2000) applies backpropagation neural network to the comparison among the plant species. Liu et al. (2001) also uses the combination of ANN and genetic algorithm to estimate the corn yield, with the input factors: temperature, rainfall, soil texture and soil PH value. Drummond (2003) also applies ANN and multiple linear regressions to compare the forecast of corn and soybean. Kuo and Liu (2000a, 2000b) uses multi-variables factor analysis and backpropagation neural network respectively to analyze the groundwater quality change of Yun-lin area in Taiwan. The results show that such two factors as seawater salination and arsenic pollution represents 78% of the influence of all 13 groundwater quality items. Chang et al. (2000) adopts fuzzy ANN to predict the flow rate at the upstream Song-mao stream measurement station of Te-chi Reservoir to offer reference for the instant operation at Te-chi Reservoir.

In Taiwan, the agricultural water use occupies the most part of whole water resource, so the accurate estimation of crop evapotranspiration helps irrigation associations to efficiently manage the limited water resource. Different from the traditional method which uses empirical formula to estimate crop evaporation, this study applies Matlab software to establish backpropagation neural network models to analyze the non-linear relationship between crop evapotranspiration and agricultural weather factors, according to which then crop evapotranspiration at different period can be predicted.

METHODOLOGY

The present research is to take the agricultural factors collected by the agricultural weather stations at Irrigation Experiment Station of ChiaNan Irrigation Association as the input layer of artificial neural networks, and the potential evapotranspiration or the pan evaporation as the output layer. After the training and learning procedures, the neural networks can be used to predict the potential evapotranspiration and the pan evaporation at a period, based on the data from the input layer of this period, together with the weight coefficients of the neural networks.

Evapotranspiration Estimation

The Irrigation Experiment Station of ChiaNan Irrigation Association (23°13'N, 120°11'E) is about 4m in altitude and 10 km away from coast. Since this area lies within the ChiaNan plain which is of flat ground and consistent climate, the information and data acquired in this area can fully represent the agricultural and production environment in ChiaNan plain area. Figure 1 shows the deployment of the central testing field and the agricultural weather stations. The devices for weather observation include dry and wet-bulb thermometers, thermometer, sunshine recorder, pyrheliometer, evaporation pan, anemometer, ground temperature indicator and pluviometer. The present research utilizes the agricultural weather data in past years recorded by the agricultural weather station, and also takes the evapotranspiration estimated by the FAO56 Penman–Monteith formula and the actual pan evaporation as the data required by the output layer of ANN. Allen et al. (1998) described the FAO56 Penman–Monteith method as Eq.(1).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o denotes the crop reference evapotranspiration (mm day^{-1}); R_n denotes the net radiation at crop surface (MJm^{-2} day^{-1}); G represents the soil heat flux density (MJ m^{-2} day^{-1}); T is the mean daily air temperature at 2 m height (°C); u_2 is the wind speed at 2 m height (m s^{-1}); e_s denotes the saturation vapour pressure (kPa); e_a represents the actual vapour pressure (kPa); e_s-e_a denotes the saturation vapor pressure deficit (kpa);Δ represents the slope vapour pressure curve (kPa $^oC^{-1}$); γ is the psychometric constant (kPa $^oC^{-1}$).

As shown in Eq.(2), the difference between the water in need by referential plants and the estimate of pan evaporation can be adjusted by the evaporation pan coefficient.

$$ET_o = K_p \times E_{pan} \tag{2}$$

where ET_o denotes the crop reference evapotranspiration (mm day^{-1}); K_p represents the evaporation pan coefficient; E_{pan} is the evaporation of evaporation pan (mm/day).

Theoretical Analysis of Backpropagation Neural Networks

The backpropagation neural network is one of the most popularly used artificial neural networks. Since it has the capability of learning and memorizing, it can be used for training and prediction. A backpropagation neural network usually has three layers: (1) an input layer to receive external information, (2) an output layer to output information to the external environment, (3) a hidden layer to supervised learning networks, which are to retrieve the training cases from the problems under investigation, to derive the underlying corresponding rules between the input variables and output variables, through minimizing the error function via the gradient steepest descent method, and finally to determine the underlying rules and estimate the new testing cases to output variables based on the memorizing capability.

During the training and learning of backpropagation neural networks, the weighing factors that are used to connect the input, output and hidden layers will change, so as to establish the nonlinear relationship between the input and output variables. The present research will utilize this property, and take the agricultural weather factors automatically recorded in the agricultural weather station as inputs to the input layer, which include the following average monthly statistics data: (1) the highest temperature; (2) the lowest temperature; (3) average temperature; (4) relative humidity; (5) wind speed; (6) sunlight hours; (7) solar radiation amount; (8) dew point; (9) forenoon ground temperature; (10) afternoon ground temperature. And also the output layer needs the potential evapotranspiration and pan evaporation. After the complete training and learning, the potential evapotranspiration or the pan evaporation during this period can be predicted based on the data in the same duration to the input layer and the weighing factors in the trained neural network model. Figure 2 shows the sketch map of backpropagation artificial neural network.

Eq.(3) denotes that the data to the input layer are converted to the range between 0~1 by the sign function during the forward stage, which in turn are regarded as the inputs to the hidden layer. Based on the calculation of Eq.(3), the values (y) transmitted from the input layer to the hidden layer can be represented in Eq.(4), while the results of (y) by Eq.(4) are taken as the input from the hidden layer to the output layer, and Eq.(5) then is used to calculate the (v) in the output layer based on the y values, and then Eq.(6) again uses a nonlinear function to convert the outputs in the output layer (v) into estimates (Z) during the forward stage, which will be compared with the target values (t) in the output layer.

$$g(u)=\frac{1}{1+e^{-u}} \qquad u=a_0+a_1*x \tag{3}$$

where x denotes the input data of input layer; a_o denotes the base weighing factor of input layer; a_1 represents the weighing factors between input and hidden layer.

$$y=g(u)=\frac{1}{1+e^{-u}} \tag{4}$$

$$v=b_0+\sum_{j=1}^{J} b_j\, y_j \tag{5}$$

$$Z = g(v) = \frac{1}{1+e^{-v}} \qquad (6)$$

where j denotes node numbers of hidden layer; b_j denotes the weighing factors between hidden and output layer; b_o represents the base weighing factor of output layer; y_j is the output values of j^{th} node within hidden layer.

As known from the flow chart of backward procedure, Eq.(7) is used to calculate the error between the outputs in the output layer (z) and the target values (t) during the backward stage. And then the training will continue till the weighing factors, which are changed accordingly, are less than the tolerance. After that, the model can be used for prediction.

$$E = \frac{\frac{1}{2}\sum_{n=1}^{N}\sum_{k=1}^{K}\left(Z_{kn} - t_{kn}\right)^2}{NK} \qquad (7)$$

where N denotes data numbers of input layer; K denotes the node numbers of output layer; b_o represents the base weighing factor of output layer; t_{kn} is the target values of the n^{th} data; Z_{kn} represents the prediction values of the n^{th} data.

The Analysis of Weighing Factors in Artificial Neural Networks

The present research uses the weighing factors to establish the weight indices of the artificial neural network, after finishing the training of the above artificial neural network model, so as to investigate the importance and influence of different input variables relative to the actual measurements. Howes and Crook (1999) proposed the use of the weighing factors in the network to measure the influence of different input variables, including three types of influence: (general influence, GI), (specific influence, SI) and (potential influence, PI), which can be used to analyze and explain the interrelation between input and output variables. In detail, GI is to quantify the different interrelation and influence between input variables/characteristics and output results, based on the whole learning and training samples; SI and PI are, instead, based on a specific prediction sample, to quantify the different interrelation and influence between input variables/characteristics and outputs. In the hypothesis in Howes and Crook (1999), as for a three-layer artificial neural network, which has an input layer of n nodes, a hidden layer of h nodes and an output layer of 1 node, the GI calculation is given in Eq.(8):

$$GI(x_i) = \frac{\sum_{j=1}^{h}\left|\left(\frac{w_{ji}}{\sum_{i=0}^{n}\left|w_{ji}\right|}\right)v_j\right|}{\sum_{j=0}^{h}\left|v_j\right|} \qquad (8)$$

where h denotes node numbers of hidden layer; n denotes the node numbers of input layer; i, j represents the index; w_{ij} is the weighing factors between the i^{th} node of input layer and j^{th} node of hidden layer; v_j represents the weighing factor of the hidden layer's j^{th} node to output layer.

RESULTS AND DISCUSSION

Evapotranspiration Estimate by the A1, A2 Groups with Ten inputs

Group A1 has an input layer with ten agricultural weather factors as its inputs, and an output layer with the evapotranspiration estimate by FAO56 Penman–Monteith formula as its single output. To achieve the best training and prediction performance in group A1, the present research tests the models of 1 to 10 nodes in the hidden layer respectively. As for group A1 with an input layer of ten agricultural weather factors and an output layer of one evapotranspiration estimate, all models constructed are the following ten types: 10*1*1, 10*2*1, 10*3*1, 10*4*1, 10*5*1, 10*6*1, 10*7*1, 10*8*1, 10*9*1, 10*10*1. From the training result, it is known the one with a hidden layer of ten nodes is of the best performance. Figure 3 shows the backpropagation neural network with an input layer of ten nodes, a hidden layer of 10 nodes and an output layer of 1 node (10*10*1). Figure 4 shows the convergence of errors of the 10*10*1 neural network model in group A1, which finally converges to 0.005. Figure 5 shows the linearly regressed values for the recored weather data by Irrigation Experiment Station of ChiaNan Irrigation Association since 2004 based on the trained neural networks model, and the correlation coefficient reaches 0.993. Figure 6 shows the variation when the evapotranspiration predictions of ChiaNan irrigated area in 2004 by the 10*10*1 model in group A1 are compared with those estimated through the FAO56 Penman–Monteith formula. As from the result analysis, the evapotranspiration in ChiaNan irrigated area in 2004 estimated by the FAO56 Penman–Monteith formula is 911.6cm, while the one predicted by the 10*10*1 model in group A1 is 896.4cm, which shows an error ratio of 1.67% only.

Group A2 has an input layer with ten agricultural weather factors as its inputs, and an output layer with pan evaporation as its single output. To obtain the best training and prediction performance, the present research separately tests different models, with the number of nodes in the hidden layer within the range from 1 to 20. That is, group A2 forms the set of 14 models in the following with an input layer of ten agricultural weather factors and an output layer of pan evaporation: 10*1*1, 10*2*1, 10*3*1, 10*4*1, 10*5*1, 10*6*1, 10*7*1, 10*8*1, 10*9*1, 10*10*1, 10*11*1, 10*12*1, 10*15*1, 10*20*1. As learned from the training result, the model with 20 nodes in the hidden layer performs best. Figure 7 shows the backpropagation neural networks model (10*20*1) in group A2, with an input layer of 10 nodes, a hidden layer of 20 nodes and an output layer of 1 node. Figure 8 shows the convergence of errors during the training of the 10*20*1 model in group A2, which converges to 0.7. Figure 9 shows the linearly regressed value for the recorded weather data by Irrigation Experiment Station of ChiaNan Irrigation Association in 2004 based on the model when the training is finished, which just has a correlation coefficient of 0.708. Figure 10 shows the variation when the evapotranspiration predictions about ChiaNan irrigated area in 2004 by the 10*20*1 model in group A1 are compared with those pan evaporation. As from the result analysis, the pan evaporation in ChiaNan irrigated area in 2004 is 1673.1cm, while the one predicted by the 10*20*1 model in group A2 is 1451.72cm, which shows an error ratio of 13.23%.

Analysis of Weighing Factors in Backpropagation Neural Network Models

After the training of backpropagation neural networks, all the weighing factors in input, hidden and output layers can be further utilized to calculate the GI values based on Eq.(8). The magnitude of GI values can be used to investigate the importance of the agricultural weather factors in the input layer to the evapotranspiration in the output layer. Since during both the training and prediction stages, group A1 shows rather high correlation, the weighing factors calculated based on Eq.(8) after the model training in group A1 has been finished are listed in Table 1. The analysis shows that wind speed has strong influence. Taking the group A1 for instance, which accepts 10 agricultural weather inputs and the output of the evapotranspiration estimate by the FAO56 Penman–Monteith formula, the influence rank in the descending order of importance according to the General Influence (GI) are: wind speed (GI=0.438)> average temperature (GI=0.204)>dew point(GI=0.162) >the highest temperature (GI=0.051)> the lowest temperature (GI=0.05)> relative humidity (GI=0.039)> forenoon ground temperature (GI=0.027)> afternoon ground temperature (GI=0.02)> solar radiation amount (GI=0.006)> sunlight hours (GI=0.002). It can be further concluded from Table 1 that the wind speed among all these agricultural weather factors affects the evapotranspiration the most significantly, followed by the average temperature, while the effects of solar radiation amount and the sunlight hours on evapotranspiration are least significant.

Table 1. The GI Values and Ranks of Ten Agricultural Weather Factors in Group A1

agricultural weather factors	GI values	Ranks
Highest temperature	0.0508	4
Lowest temperature	0.0503	5
Average temperature	0.2041	2
Relative humidity	0.0392	6
Wind speed	0.4383	1
Sunlight hours	0.0058	10
Solar radiation	0.0022	9
Dew point	0.1622	3
Forenoon ground temperature	0.0269	7
Afternoon ground temperature	0.0202	8

Comparison of Optimal Backpropagation Neural Networks in Different Groups

The correlations of training and prediction when using the evapotranspiration quantity calculated by the FAO56 Penman–Monteith formula as the target outputs during the training and prediction are above 0.97, which indicates that the degree of consistency between the values by FAO56 Penman–Monteith formula and the predicted ones is very high; on the contrary, the correlation coefficient of training and prediction, when using the pan evaporation as the target outputs, are significantly lower than those with the target outputs from the empirical FAO56 Penman–Monteith formula. The correlation coefficients in training and prediction stage by the group A2 are 0.887 and 0.708, respectively.

As observed from the training mode, whatever the group is, the correlation coefficient will decrease and the mean square error will increase as the number of input factors decreases; and the correlation coefficient will increase when there are more nodes in the hidden layer. As observed from the prediction mode, the slope is most likely larger than 1, which means that most predicted values are less than the actual ones, that is to say, the predicted values underestimates the actual ones. The underlying reason may lie in the difference in the target outputs, which causes the difference in correlation coefficient. When the target outputs are values calculated through the FAO56 Penman–Monteith formula, the training mode is simulating the formula since it has a strong ability in fitting the data. After the model is constructed, it becomes a formula calculator, thus has large correlation coefficient; When the target outputs are values based on pan evaporation, the training performance is poor and the correlation coefficient are lower than those based on FAO56 Penman–Monteith formula, because the pan evaporation is a measurement rather than a calculated one, and is more complicated than those derived from the FAO56 Penman–Monteith formula.

The predictions to the evapotranspiration in ChiaNan irrigated area in 2004 based on the neural network models after training has been compared. The evapotranspiration quantity in ChiaNan irrigated area in 2004, as calculated through the FAO56 Penman–Monteith formula, is 911.63cm, while those predicted through the backpropagation neural networks is 896.41 cm in group A1, with the error ratios to the calculated ones being 1.67%. In addition, the evaporation in ChiaNan irrigated area in 2004 is 1673.11cm, as from the records based on pan evaporation, while those predicted by the backpropagation neural networks is 1451.72 cm in group A2, with the error ratios to the actual one being 13.23%.

The evapotranspiration in 2004 as estimated by the FAO56 Penman–Monteith formula based on the agricultural weather information recorded by the Irrigation Experiment Station of ChiaNan Irrigation Association is 911.63 cm, while the pan evaporation is 1673.11cm. The two have the ratio of 0.777, that is to say, the evaporating pan coefficient (Kp) in ChiaNan irrigated area is 0.777.

REFERENCES

Allen, R.G., et al., 1998. FAO56: Crop Evapotranspiration- Guidelines for Computing Crop Water Requirements. FAO of UN, Rome, Italy.

Burks, T.F. et al., 2000. Backpropagation Neural Network Design and Evaluation for Classifying Weed Species Using Color Image Texture. Transactions of the ASAE, 43(4), 1029-1037.

Chang, F.J. et al., 2000. Counterpropagation Fuzzy-Neural Network for Reservoir Inflow Prediction. Monthly Journal of Taipower's Engineering, 618, 7-19.

Drummond S.T. et al., 2003. Statistical and Neural Methods for Site-Specific Yield Prediction. Transactions of the ASAE, 46(1), 5-14.

Han, H., Felker, P., 1997. Estimation of Daily Water Evaporation using an Artificial Neural Network. J. of Arid Environments, 37, 251-260.

Irmak, S., Allen, R.G., Whitty, E.B., 2003a. Daily Grass and Alfalfa-Reference Evapotranspiration Estimates and Alfalfa-to-Grass Evapotranspiration Ratios in Florida. J. of Irrigation and Drainage Engineering of ASAE, 129(5), 360-369.

Irmak, S., Allen, R.G., Jones, J.W., 2003b. Solar and Net Radiation-Based Equations to Estimate Reference Evapotranspiration in Humid Climates. J. of Irrigation and Drainage Engineering of ASAE, 129(5), 336-347.

Kuo, Y.M., Liu, C.W., 2000a. Analysis on Variation of Groundwater Quality in Yun-Lin Coastal Area:(1) Multivariate Factor Analysis Method. Taiwan Water Conservancy, 48(1), 1-8

Kuo, Y.M., Liu, C.W., 2000b. Analysis on Variation of Groundwater Quality in Yun-Lin Coastal Area:(2) Back-Propagation Artificial Neural Network Method. Taiwan Water Conservancy, 48(1), 9-25.

Liu, J., Goering, C.E., Tian, L. 2001. A Neural Network for Setting Target Corn Yields. Transactions of the ASAE, 44(3), 705-713.

Yang, C.C. et al., 1997. Application of Artificial Neural Networks for Simulation of Soil Temperature. Transactions of the ASAE, 40(3), 649-656.

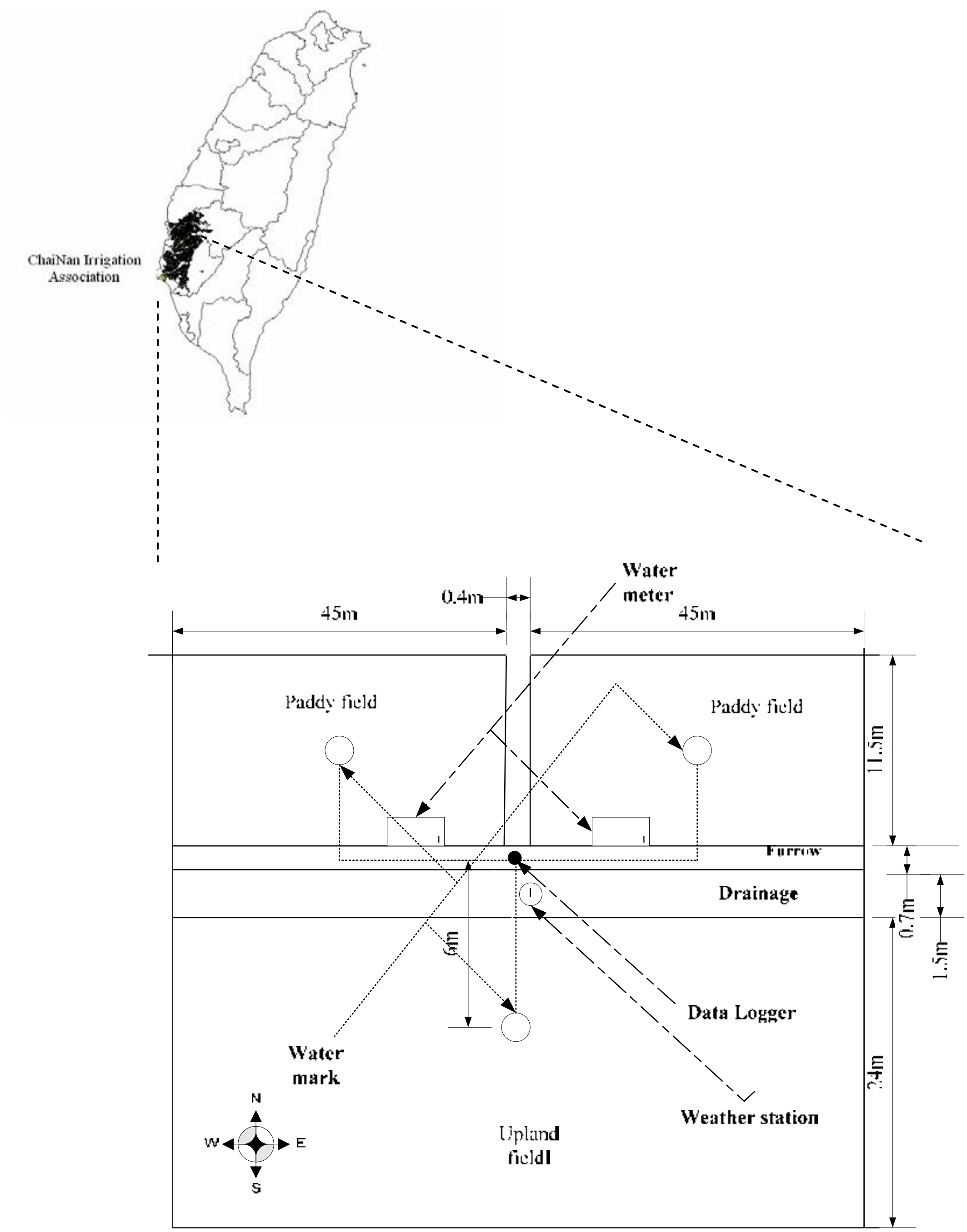


Figure 1. The Ichnography of the Irrigation Experiment Station of ChiaNan Irrigation Association

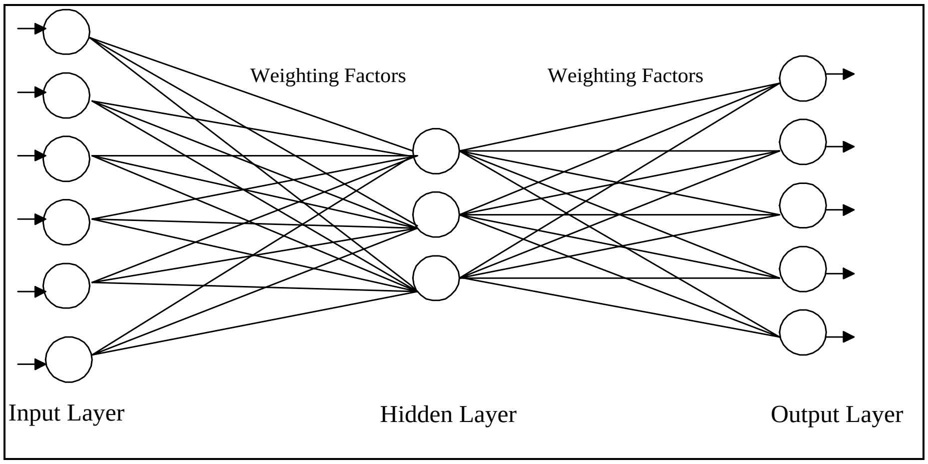


Figure 2. The Diagram of Bbackpropagation Artificial Neural Networks

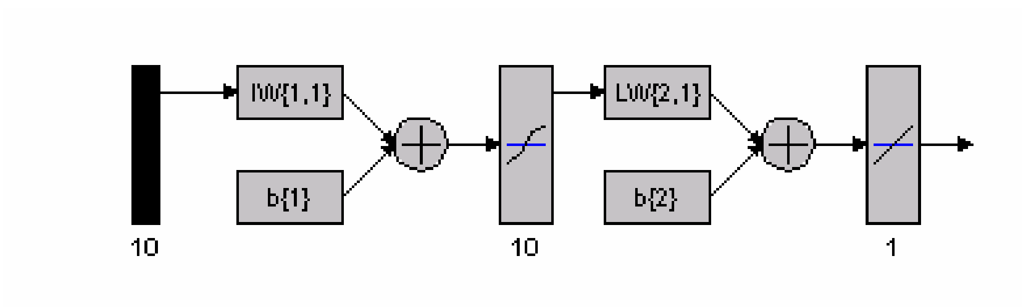


Figure 3. The Diagram of the Backpropagation Neural Network with an Input Layer of 10 Nodes, a Hidden Layer of 10 Nodes and an Output Layer of 1 Node

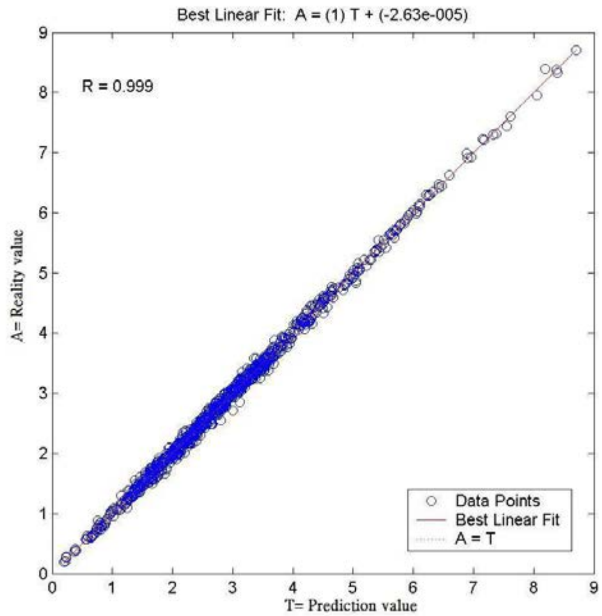


Figure 4. The Linear Regression Values after the Training of the 10*10*1 Model in Group A1

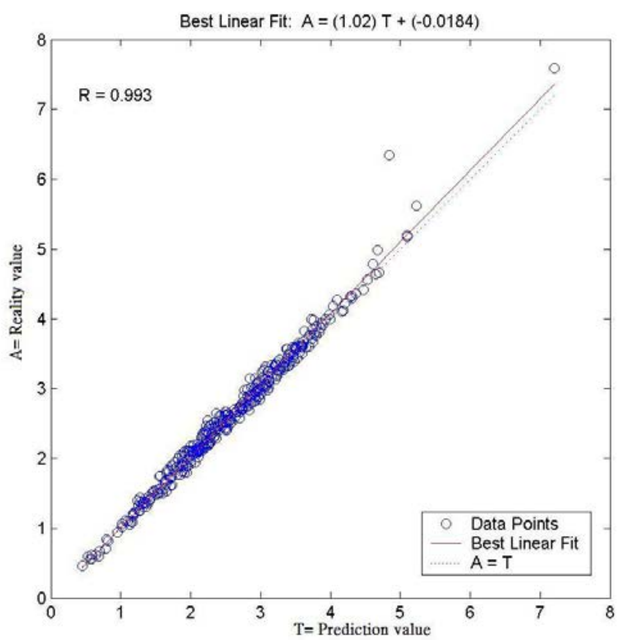


Figure 5. The Linearly Regressed Predictions to the Evapotranspiration in ChiaNan Irrigated Area in 2004 by the 10*10*1 Model in Group A1

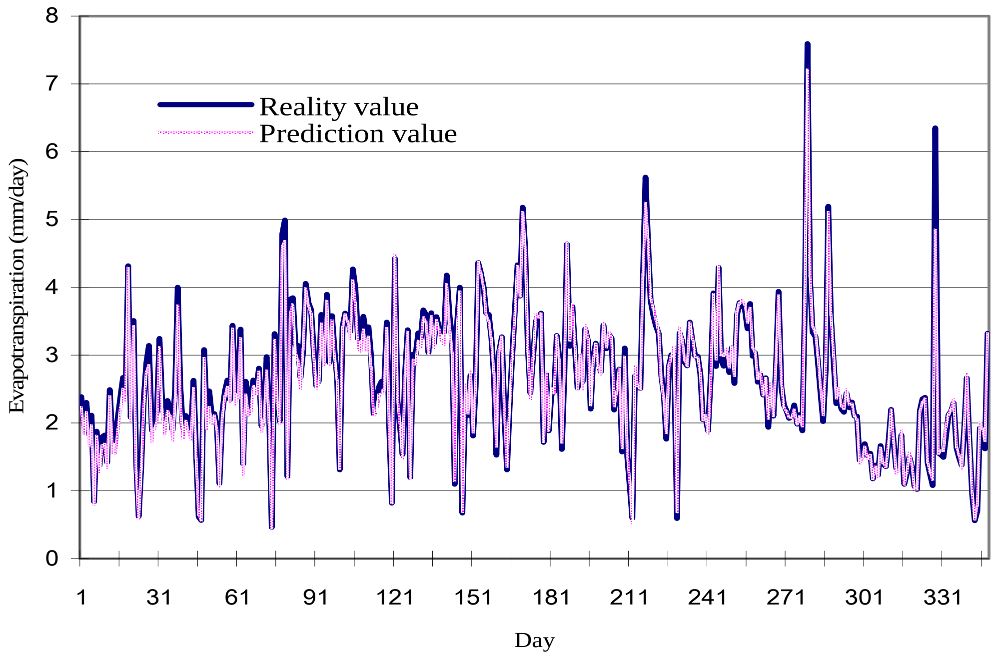


Figure 6. Comparison Between the Predicted Evapotranspiration in 2004 by the 10*10*1 Model in Group A1 and the One Estimated by FAO56 Penman-Monteith Method

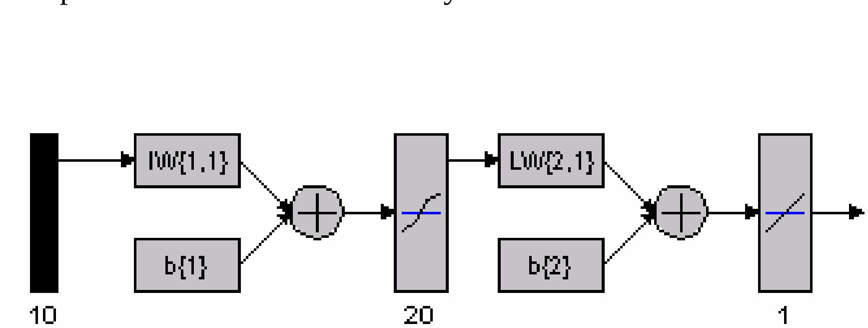


Figure 7. The Backpropagation Neural Network with an Input Layer of 10 Nodes, a Hidden Layer of 20 Nodes and an Output Layer of 1 Node in Group A2

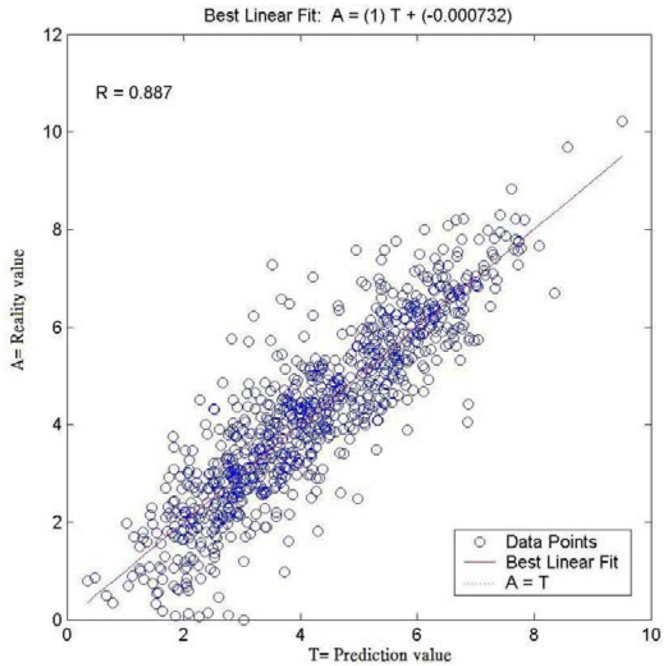


Figure 8. The Linear Regression Values after the Training of the 10*20*1 Model in Group A2

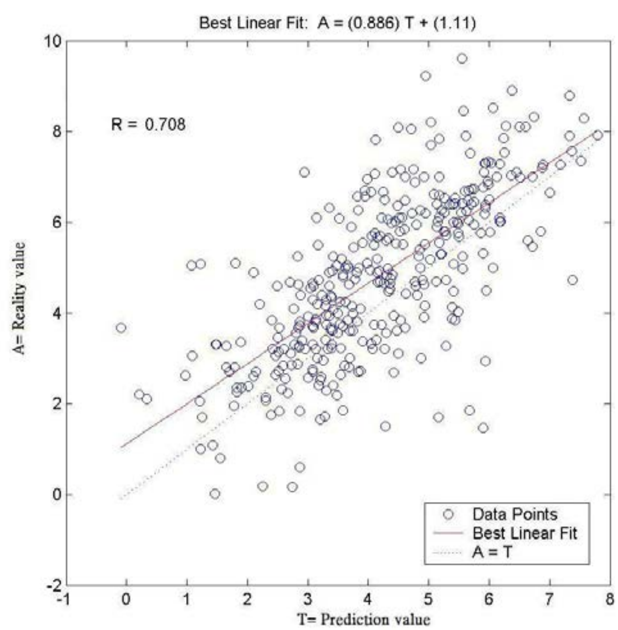


Figure 9. The Linearly Regressed Predictions to the Evaporation in ChiaNan Irrigated Area in 2004 by the 10*20*1 Model in Group A2

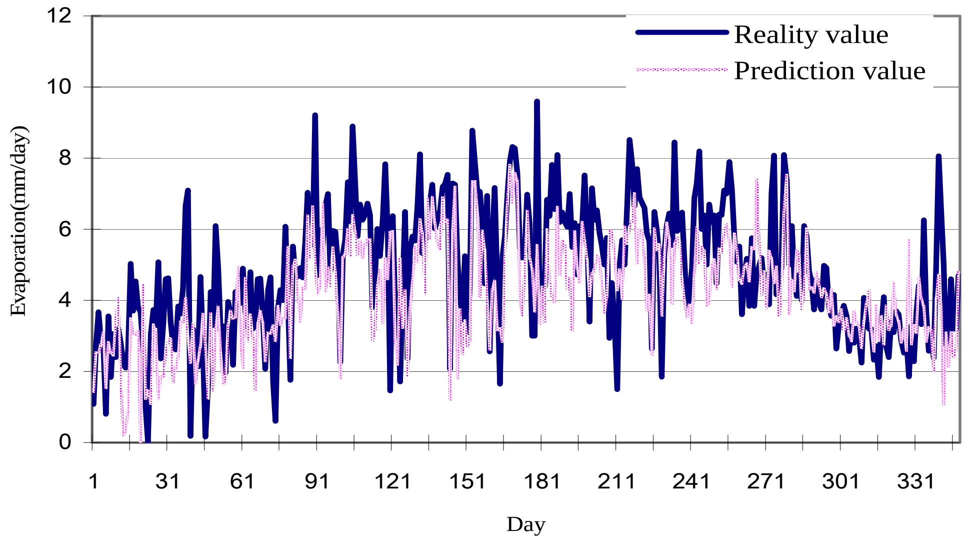


Figure 10. Comparison Between the Predicted Evaporation in 2004 by the 10*20*1 Model in Group A2 and the One Estimated by FAO56 Penman-Monteith method

INFLUENCE OF HIGH-TURBID INFLOW ON WATER SUPPLY IN THE SHIHMEN RESERVOIR

Fong-Zuo Lee[1]
Jihn-Sung Lai[2]
Gwo-Wen Hwang[3]
Yih-Chi Tan[4]

ABSTRACT

The Shihmen reservoir is a multi-functional reservoir and its functions include irrigation, water supply, hydroelectric power, flood prevention and sightseeing. The major allocation of registered water rights for irrigation and water supply are 43.28% and 20.96%, respectively. In 2004, Typhoon Aere attacked Taiwan and generated more than 973 mm rainfall within 4 days in the watershed of the Shihmen reservoir. Highly turbid inflows affected the water supply system seriously. Sediment concentration of the inflow water in the Typhoon Aere rose to 242,000 Nephelometric Turbidity Unit (NTU) and was far-exceeded water treatment capacity which can only handle 6,000 NTU. Such high sediment concentration caused a loss of water supply for two weeks in the Taoyuan area. A three-stage water intake has been designed to divert lower turbidity water at various water levels. Based on field measured data, a 3D numerical model is employed to simulate velocity and concentration phenomenon in the reservoir to provide guidance for operation timing for allocating public water supply and irrigation water.

INTRODUCTION

Taiwan is situated at a geographical location with special climatic condition that brings to the island 3.6 typhoons per year on the average. These typhoons often result in flood disasters that can cause serious damage to properties and sometimes with severe casualties. However, they also bring rainfall as a valuable water resource. In 2004, Typhoon Aere attacked north Taiwan and the Shihmen reservoir water supply suffered from a shortage for 14 days. The Shihmen reservoir has acted as the primary and most important infrastructure of water resource development over the past forty years in Taiwan. As livelihood and industrial water needs are increasing, the water supply demand of the Shihmen reservoir is rising. Recently, typhoons such

[1]Ph. D. Student, Dept. of Bioenvironmental Systems Eng. , National Taiwan University, Taipei City, 106, TAIWAN, R.O.C., E-mail:d94622004@ntu.edu.tw
[2]Associate Research Fellow, Hydrotech Research Institute and Associate Professor, Department of Bioenvironmental Systems Eng. , National Taiwan University, Taipei City, 106, TAIWAN, R.O.C., E-mail:Jslai525@ ntu.edu.tw
[3]Research engineer, Hydrotech Research Institute and Ph. D Student, Dept. of Civil Eng. , National Taiwan University, Taipei City, 106, TAIWAN, R.O.C., E-mail:gwhwang@ntu.edu.tw
[4]Vice Chairperson WG-ENV, ICID. SG, Chinese Taipei Committee, ICID
Director, Hydrotech Research Institute and Professor, Dept. of Bioenvironmental Systems Eng., National Taiwan University, Taipei City, 106, TAIWAN, R.O.C., E-mail:yctan@ntu.edu.tw

as Typhoon Haitang (2004) and Typhoon Talim (2005) brought high sediment concentration inflow into reservoir to cause serious deposition problem and water supply shortage. The Water Resources Agency has established a temporary pumping station with capacity 3x10^5 CMD on the top of the Shihmen dam to divert near surface lower-turbidity water that the water treatment plant can accommodate. The temporary pumping station was installed after Typhoon Aere as shown in Fig.1.

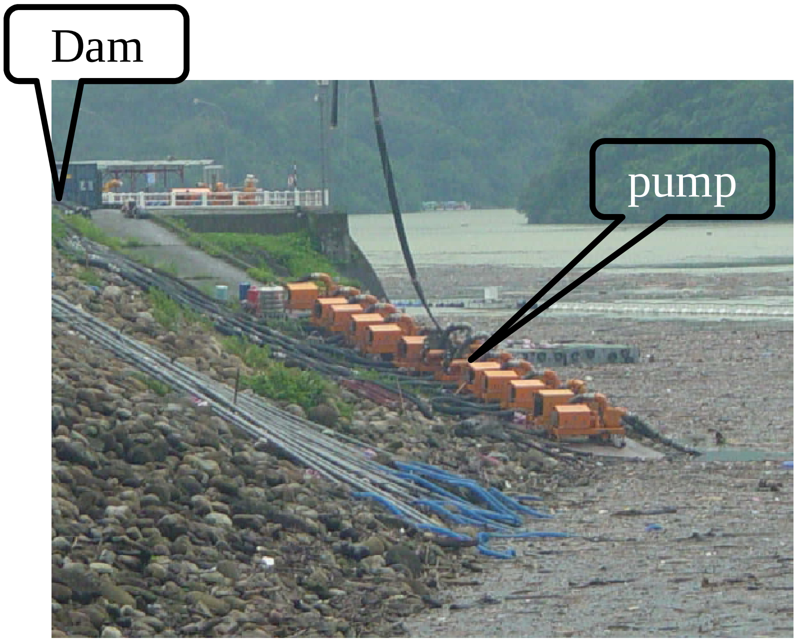


Figure1. Temporary pumping station on the top of Shihmen reservoir (after Typhoon Aere)

This study presents two sets of measured data from Typhoon Aere and Typhoon Talim in the Shihmen reservoir [4]. The 3D CFD numerical model, CFX [1], is used to describe the turbid flow phenomenon of the concentration and velocity distribution in the Shihmen reservoir.

DESCRIPTIONS OF THE SHIHMEN RESERVOIR

The Shihmen reservoir has a natural drainage area of 762.4 km^2. It is formed by the Shihmen dam located at the upstream reach of the Dahan River and flows westward to the Taiwan Strait. A map of the watershed area of the Shihmen reservoir is presented in Fig. 2. Based on hydrological analysis, the design flood discharges for 100-yr and 200-yr return-period floods are 8,703 and 9,008 m^3/s, respectively, as listed in Table 1. The Shihmen dam constructed in 1963 is a 133.1m high and 360m wide embankment dam with spillways, permanent river outlet, power plant intakes and flood diversion tunnels controlled by tailrace gates. The elevations of the spillway crest, permanent river outlet, power plant intakes and flood diversion tunnels are EL.235 m, EL.169.5m, EL.173m and EL.220m, respectively. The design capacity of the three spillways is 11,400m^3/s, the permanent river outlet is 34m^3/s, the power plant intake is 137.2m^3/s, and flood diversion tunnel is 2,400m^3/s. With a maximum water level of EL.245m, the reservoir pool is about 16.5km in length and forms a water surface area of 8.15km^2. The initial storage capacity was 30,912x 10^5 m^3, and the active storage was 25,188x 10^5 m^3. Based on the historical records of water levels at the Shihmen dam, the month average water stages of the reservoir at the dam from 1985 to 2005 are plotted for each year in Fig. 3. Due to a lack of desiltation facilities, incoming sediment particles have settled down rapidly along the reservoir since the dam was completed. Based on the survey data, the longitudinal bed profile along the reservoir is plotted in Fig. 4. As shown in Fig. 4, the Shihmen reservoir has accumulated a significant amount of sediment after dam completion. The depositional pattern has become wedge-shaped since 2000. From recent survey data in 2005, the storage capacity was estimated to be 72.06% of its initial capacity. Based on size distribution shown in Fig.5, the sediment deposits are classified as silt or clay.

Table1. Peak flow of return-period in Shihmen reservoir (Unit：$10^3 m^3/s$)

return-period(year)	2	5	10	25	50	100	200
Peak flow	2,000	3,748	4,000	4,565	5,809	8,703	9,008

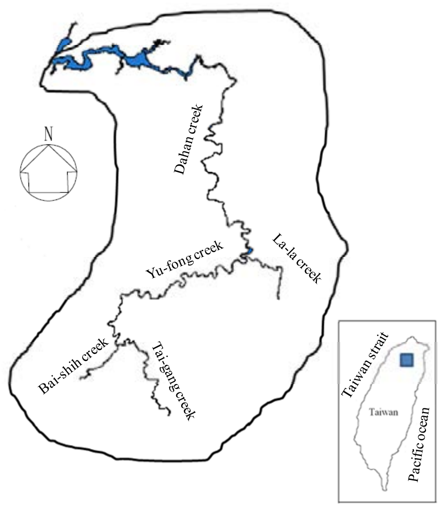


Figure 2. Watershed area of Shihmen reservoir

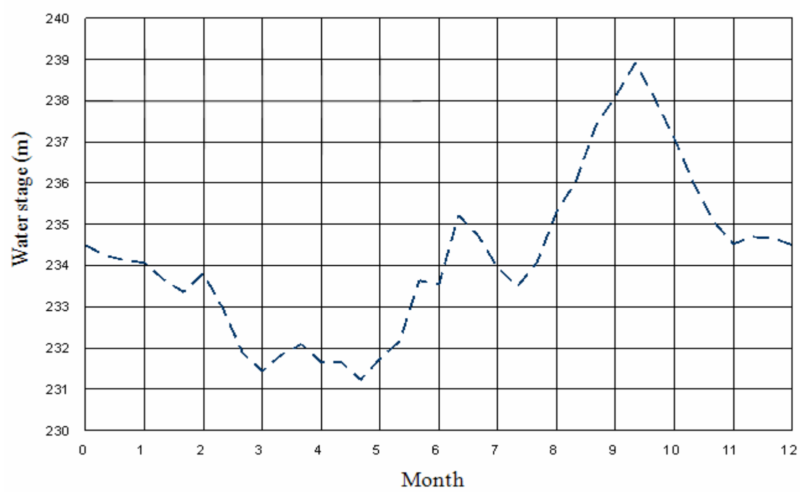


Figure 3. Month average water stage in Shimen reservoir from 1985 to 2005

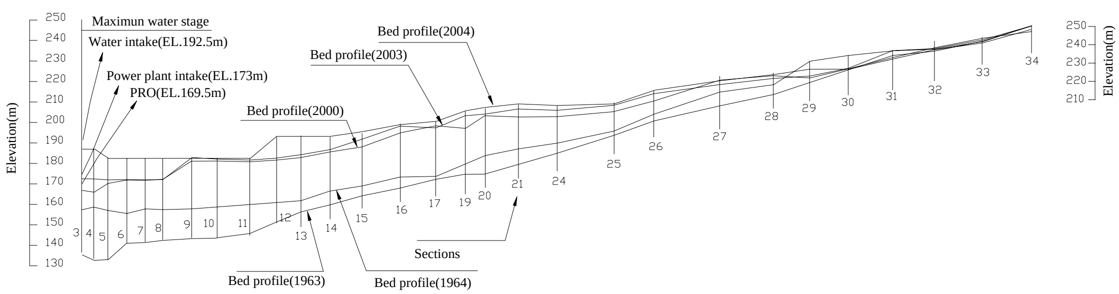


Figure4. Longitudinal variation profile of Shimen reservoir bed

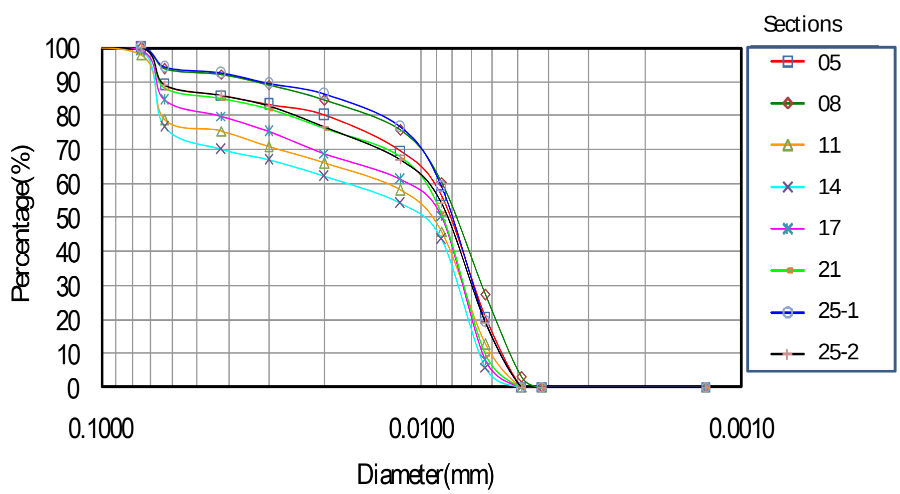


Figure 5. Sediment size distribution

The Shihmen reservoir is a multi-functional reservoir and its functions include irrigation, water supply, hydroelectric power, flood prevention and sightseeing. The water usage of the Shihmen reservoir per year is presented in Fig. 6. The irrigation area includes Taoyuan, Hsinchu and Taipei for a total of 36,500 ha, which means it is a major contributor in helping boost the agricultural productive levels in these areas. The reservoir supplies water to 28 districts and 3.4 million people. This makes it a very important water resource for the livelihood of the people in the northern Taiwan. Making use of the water impoundment at Shihmen dam, the Shihmen Power Plant generates 200 million units power annually, a vital contribution to help meet the electric power demand and boost industrial development. The reservoir main function is to prevent or improve the rapid descent rates of the upper tributaries, reducing the effect of peak flood cresting, and protecting the areas below, such as the Taipei floodplain, from waterborne disaster. The lake and mountains of the surrounding area make for a beautiful perspective and ideal spots are allowed for water-related recreation. The setting undergoes seasonal transformations, providing a natural drama with change after change in backdrop, for a scenic area that is unparalleled elsewhere [3].

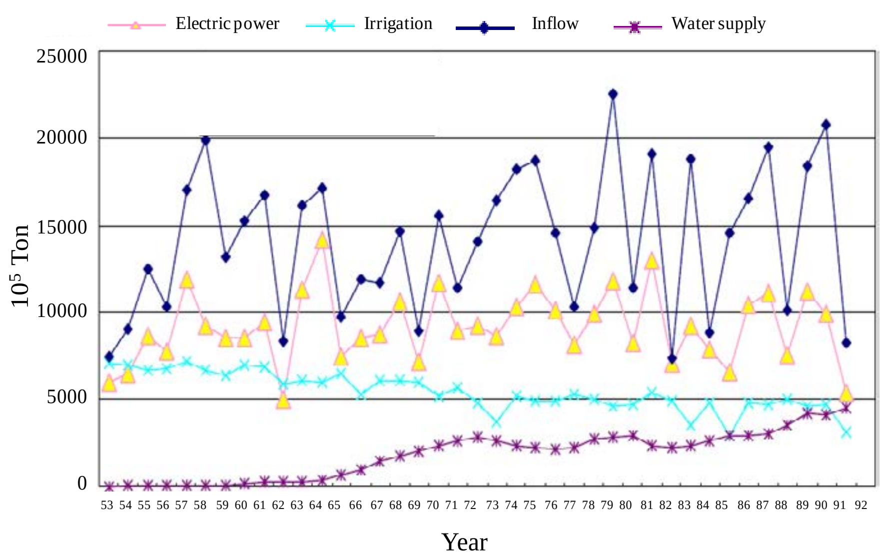


Figure 6. Amount of water usage per year for various functions

INFLUENCE OF HIGH-TURBID INFLOW

In 2004, Typhoon Aere attacked northern Taiwan and caused substantial losses. Typhoon Aere brought into the Tamshui River Basin a total rainfall of 973mm in 4 days (about 40% of the mean annual rainfall of the basin). The extremely heavy rainfall induced high turbidity in the runoff entering the Shihmen reservoir, as shown in Fig. 7[2]. The turbidity was far beyond the purification capability of the water treatment plants in the downstream area. As a consequence, 2 million residents in the Taoyuan County suffered from a shortage of water supply for 17 days.

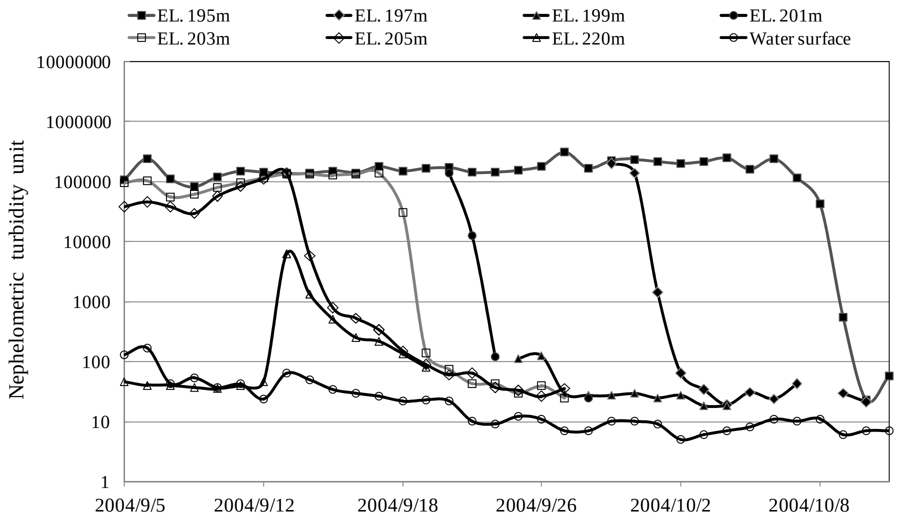


Figure 7. Sediment concentration hydrograph at water intake during Typhoon Aere

The excessive rainfall induced serious landslides in an area of 265 ha in the Shihmen reservoir watershed. That heavy rainfall generated high sediment concentration due to the runoff entering the reservoir. The main composition of the geology of Shihmen reservoir watershed is shale, which can be weathered easily and is the main source of the fine-grain clay. This geological composition further deteriorated the quality of stream flow and sustained the turbidity in the reservoir for longer period of time during the Typhoon flood. Before the attack of Typhoon Aere, detention basins behind many sabo dams had been nearly filled to their capacity. In addition, the volume of landslide caused by Typhoon Aere far-exceeded the remaining capacity of the sediment retaining basins. The facilities to divert water from the reservoir are located at lower levels. In the Typhoon Aere induced high-turbid event, the turbidity at lower level of Shihmen reservoir reached 242,000 NTU, which is beyond the maximum turbidity that water treatment plants can handle. Due to the limitation of the water conveying capacity, the water treatment plants in its neighboring counties can only supply limited amount of the water needed. So, the highly turbid inflow concentration was seriously creating not only public water supply but also sediment deposition problems. Fig. 7 presents the turbidity variations in Typhoon Aere. Then, the sediment concentration decreased to 6,000NTU which the water treatment plant can handle at water intake (EL.192.5m). A similar situation happened in Typhoon Talim(2005), as shown in Fig. 8. The Fig. 8(a) shows the flow discharge at Lungchuwan and turbidity data at EL.204m against time. The Fig. 8(b) shows the measured concentration data at water intake and this data can be used to numerical simulation.

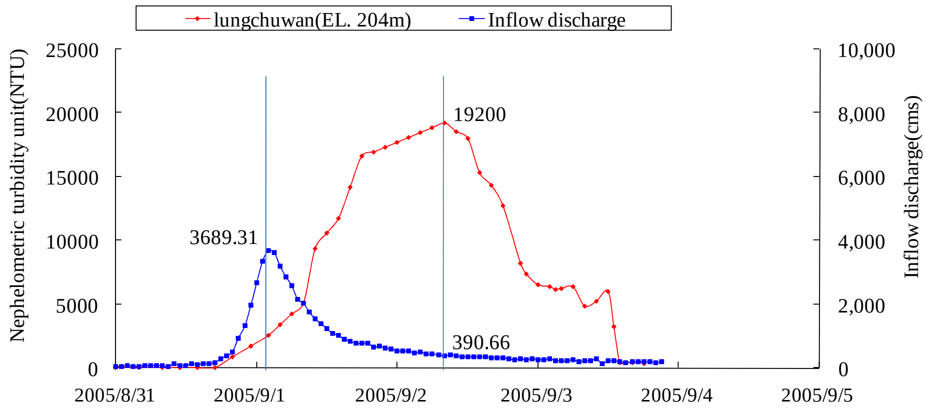


Figure 8(a). Inflow discharge and sediment concentration hydrograph at Lungchuwan

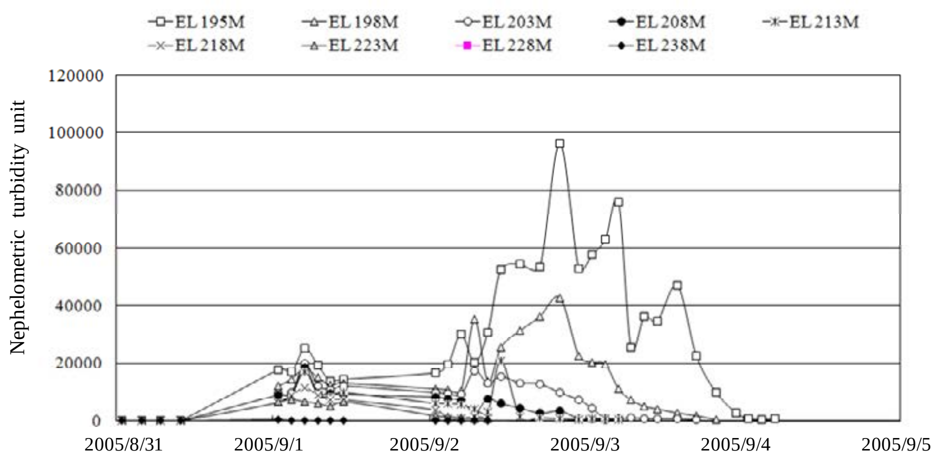


Figure 8(b). Sediment concentration hydrograph at water intake during Typhoon Talim

SIMULATION OF FLOW FIELD AND SEDIMENT DISTRIBUTION

In general, there are various models for simulating turbidity current movement [2]. One can solve fluid equations of motion with advection-diffusion equation to obtain the flow field and concentration distribution. This method does not consider the momentum exchange between fluid and sediment and the boundary condition of the bed was difficult to deal with. One may also solve fluid equations of motion with Lagrange particle transport equation and multi-phase fluid equations with volume of fraction (VOF) for each phase. Considering the efficiency and acceptable precision of simulation results, the Algebraic-Slip Model (ASM) model of CFX was adopted to simulate turbidity current movement in the Shihmen reservoir because the CFX model contained the above mentioned method and had friendly user windows. In principle, when calculating disperse multi-phase flows with very fine particles (e.g. reservoir sediment) the relaxation time for the particles will be much smaller than the flow time scale. If the disperse phases are at low volume fractions, it is then unnecessary to solve momentum equations for the particle phase separately, as it can be assumed that the particles are always at their terminal velocity (settling velocity). So, the ASM model was suited to estimate lower concentration flow field [2]. The boundary condition of the bed is set to be a no slip condition, and the free surface was rigid-lid approximation. The governing equations are written as follows:

- Conservation of mass:

$$\nabla \bullet (u_i) = 0 \tag{1}$$

- Conservation of momentum:

$$\frac{\partial}{\partial t}(u_i) + \nabla \bullet \left(u_i \times u_j + \frac{p}{\rho}\delta_{ij} - \mu\left(\nabla u_i + (\nabla u_i)^T\right)\right) = \frac{\Delta\rho}{\rho} g_i \tag{2}$$

- Conservation of sediment mass:

$$\frac{\partial}{\partial t}(c) + \nabla \bullet \left(c(u_i - \omega) - \Gamma \nabla c\right) = 0 \tag{3}$$

where u_i and u_j = velocity vector components； p = pressure； $\rho = c\rho_s + (1-c)\rho_w$ ； c = sediment concentration； ρ_s = sediment density； ρ_w = fluid density； δ_{ij} = Kronecker Delta； μ = viscosity； $\nabla\rho = \rho - \rho_w$ =density variation； g_i =gravity components； ω = settling velocity, and Γ = diffusion coefficient.

According to Talim typhoon measured data, we established simulation area within the domain near dam from Section 14 to the dam. The simulation domain is represented in Fig. 9. Fig. 10 shows the simulated results of concentration distribution and velocity field. Fig. 10(a) presents that the sediment concentration spreads after the flow is flowing through the bend after section 11, as shown in the concentration spreading area (section 10). The velocity decreases after the bend due to wider cross section, as shown in Fig. 10(b). The simulation result at EL.204m is about 16,000NTU (as shown) and the measured data at water intake is about 17,400NTU. So, the simulation results can provide the prediction of concentration and velocity distributions to estimate the sediment concentration of the outflows at spillway or water intake.

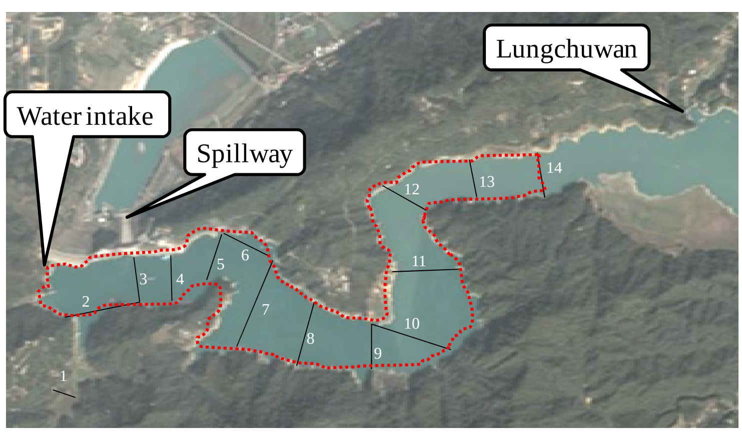


Figure 9. Simulation area

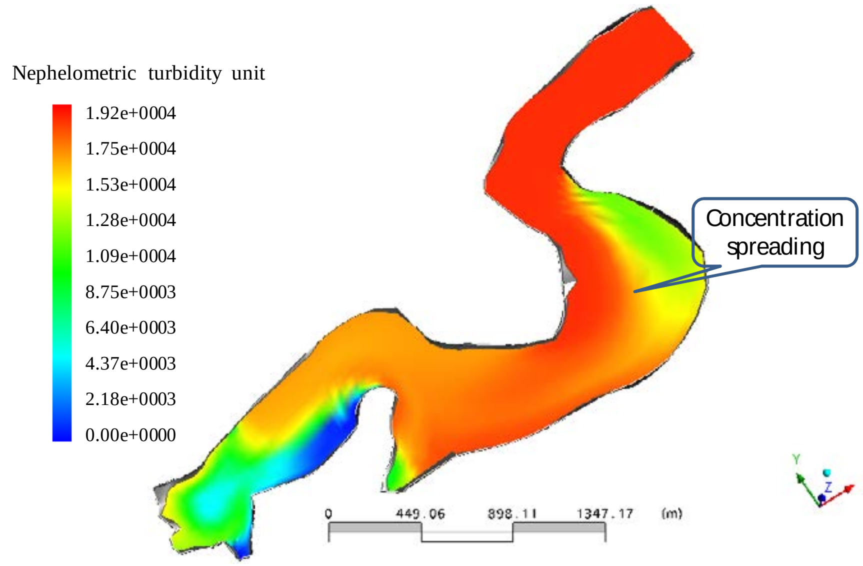


Figure 10(a). Simulation of sediment concentration distribution

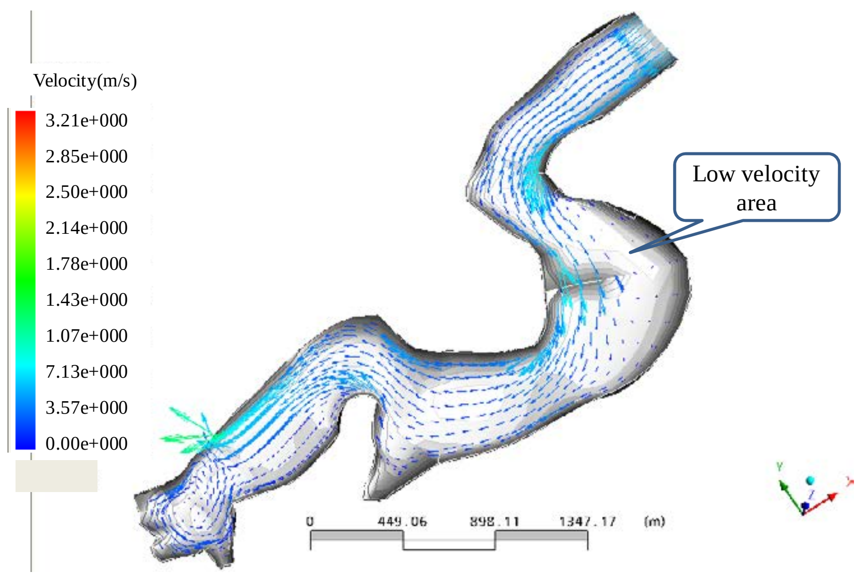


Figure 10(b). Simulation of velocity distribution

CONCLUSIONS

Due to highly turbid inflow problems in the Shihmen reservoir, the operation of sediment sluicing and sediment concentration monitoring are essentially important. The real-time prediction of water allocation for irrigation and water supply is necessary. Therefore, the 3D CFX numerical model is adopted to simulate the turbidity current flow phenomenon and predict the sediment concentration distribution near the intakes of the power plant. The calculated results can provide the information of operation timing for allocating public water supply (if sediment concentration $\leq$ 6,000 NTU) and irrigation water (if sediment concentration $\leq$ 10,000 NTU).

REFERENCES

1. CFDS-CFX4 Release 4.1, user guide. (1995). Computational Fluid Dynamics Services, Harwell Lab., Oxfordshire, U. K.

2. Lai, J. S. (2006) "*A Study of Density Current and Operation of Reservoir Desiltation*", Hydrotech Research Institute, NTU, Report No. 692.(in Chinese)

3. Please refer to Northern Region Water Resources Offices, Water Resources Agency, Ministry of Economic Affairs (http://www.wranb.gov.tw/wranb_spring/wranb_eng/contents/shihmen.asp)

4. Sung, C. C. (2006) "The Study on the Design and Development of the Ultrasonic Suspended Load Concentration and Flow Velocity Measuring Instrument for Reservoir", Hydrotech Research Institute, NTU, Report No. 680. (in Chinese)

SOIL SALINITY INFLUENCE TO CROP YIELD, WATER CONSUMPTION AND HYDRAULIC RESISTANCE

Atsushi Marui[1]
Aimin Hao[2]
Tomokazu Haraguchi[3]
Yoshisuke Nakano[4]
Koji Inosako[5]

ABSTRACT

The cultivation experiment about plant response to salinity stress was conducted to clarify the relationship between water consumption and hydraulic resistances by studying plants grown in soils with some different salinity concentrations. To determine the hydraulic resistance of each part of the plant, the potentials at the leaf, stem, and root were measured by using a psychrometer, and the amount of transpiration was also measured. As the concentration of the NaCl solution was 0.03 mol/L, the decrease percentage of transpiration was 15.2% compared with the case of distilled water. The decrease percentages were 43.0% and 53.1% at 0.05 mol/L and 0.07 mol/L, respectively. These decreases adversely affected water absorption. The percentages of transpiration were 59.7% and 63.0% at 0.10 mol/L and 0.15 mol/L, respectively. There was a larger decrease in transpiration. Hydraulic resistance increased rapidly when soil salinity exceeded 0.10 mol/L. And it is clear that the disorder of absorbing water by increase of the salt concentration of the soil did not have an influence on a fall of water potential of a leaf, from results of the water potential measurement at each part of crop. It is judged that the maintenance of potential in a leaf was performed by confinement of a pore. It is clear that water potential of a stem decreased with a rise of the soil salt concentration.

INTRODUCTION AND BACKGROUND

Soil salinity is the most prevalent and widespread problem that limits crop production. There are no arid areas in Japan. However, in agricultural fields that have been newly developed by reclaiming land from the sea, the productivities of crops are affected by the salt remaining in the soil. Moreover, a high concentration of salt water below the root zone will potentially move upward by capillary action and damage the crops. The greenhouse culture sometimes suffers from salt problems because the climatic conditions are similar to those in arid areas.

[1] Research associate; Laboratory of Irrigation and Water Utilization, Division of Regional Environment Science, Department of Bioproduction Environmental Science, Faculty of Agriculture, Kyushu University; 6-10-1 Hakozaki, Higashi-ku Fukuoka 812-8581, Japan;maruiuos@mbox.nc.kyushu-u.ac.jp
[2] Graduate student; Kyushu University;aimin@bpes.kyushu-u.ac.jp
[3] Research associate; Laboratory of Agricultural Water Supply and Management, Department of Agriculture Science, Faculty of Agriculture, Saga University
[4] Professor; Faculty of Agriculture, Kyushu University
[5] Associate professor; Faculty of Agriculture, Tottori University

The movements of salt and water in soils have been studied and reported by Shainberg and Shalhevet (1984), Hillel (1977), Bresler (1973), Russo and Dagon (1993), etc. Water transport in plants and soil is logically expressed using the SPAC model. Many models such as those by Cowan (1964) and Hillel (1977) have been proposed. In these models, the hydraulic resistance is represented as the resistance of the soil water flux, which can be defined as the ratio of the flow path length to the hydraulic conductivity. This resistance depends on the characteristics of the root system, the soil moisture content, and on some stress.

The effects of salt on many crops were studied by Hanks (1984), Meiri (1984), etc. Soil salinity causes two types of stresses, namely, a salinity stress due to the osmotic pressure at the root and an ion stress in a crop. These stresses decrease the water consumption of crops; therefore, they cause a decrease in the crop yield. In order to explain the relation between some stresses and water flow in crops, the hydraulic resistance was presented. For example, Longstreth (1979) studied mesophyll resistances under the NaCl treatment condition, and Amer (2004) studied the canopy resistance.

In this study, the hydraulic resistances of roots, crowns, stems, and leaves are examined by a pot experiment using a certain amount of NaCl treatment soil. The SPAC model presented in this study has three characteristics. First, in this model, water and solute movements are taken into account. Second, in order to simulate the net-type root system, a parallel resistance model is introduced. Third, the positions of the stem and leaves from the soil surface are used as inputs to this model. Finally, experiments are specially designed to clarify the effects of the solute on plant activities. The results of the water potential in the plant system obtained by the experiments and SPAC model are compared and discussed.

MODEL FOR WATER AND SOLUTE MOVEMENT

Water Flow in Plant and Soil

The soil water flow can be expressed by the following equations:

$$q = -K(\theta)(\frac{\partial \psi_m}{\partial z} + 1) \tag{1}$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(D\frac{\partial \theta}{\partial z}) + \frac{\partial K}{\partial z} - S_w \tag{2}$$

where q is the soil water flux; $K(\theta)$, the hydraulic conductivity; θ, the volumetric soil water content; ψ_m, the matric potential; D, the soil water diffusivity; t, the time; z, the depth; and S_w, the water intake rate of the roots.

The root system can be separated into a certain number of blocks to calculate the water absorption from each depth. When the roots are distributed in soil with the net-type root system, the blocks at each depth are connected directly to the crown of the stem. The water flow in this system can be expressed by using resistances in an electric circuit. The roots are represented by absorption and conduit resistances connected in a straight circuit. On the other hand, each root block is connected as a parallel circuit. These systems can be expressed by the following equations.

Water fluxes from the soil to the roots and from the roots to the crown, denoted by eq.(3) and eq.(4), respectively, are expressed as follows:

$$q_s = \frac{\psi_s - \psi_r}{R_a} = \frac{\Delta\psi_p}{R_a} \tag{3}$$

$$q_r = \frac{\psi_r - \psi_c}{R_b} = \frac{\Delta\psi}{R_b} \tag{4}$$

For the net-type root system, the total resistance through the soil to the crown can be expressed as

$$R_{ri} = R_{ai} + R_{bi} \tag{5}$$

$$1/R = \Sigma 1/R_{ri} \tag{6}$$

where R_{ri} is the resistance at the i th depth and R is the total resistance.
By substituting eq.(3) and (4) into (5) and using eq.(6), R can be expressed as

$$R = (\Sigma \frac{q_{ai}q_{bi}}{q_{bi}\psi_{si} - (q_{bi} - q_{ai})\psi_{ri} - q_{ai}\psi_c})^{-1} \tag{7}$$

The water potential (ψ_{st}) in the stem is given by

$$\psi_{st} = \psi_c - q_{ct}R_{st} \tag{8}$$

where ψ_c is the crown potential and R_{st} is the stem resistance. The flux in the leaves at a height i can be expressed as

$$q_{li} = \frac{\psi_{st} - \psi_{li}}{R_{li}} \tag{9}$$

where q_{li} is equal to the transpiration in each leaf. The total flux of the stem is the summation of eq.(9) from the bottom to the top leaves. Finally, the total transpiration rate Tr can be obtained as

$$Tr = \sum \frac{\psi_c - q_{st}R_{st} - (\psi_l)_i}{(R_l)_i} \tag{10}$$

To solve this equation, the input plant and soil resistances, and the initial condition of the soil are specified. Then, the input transpiration rate at step t set, the plant water potential is calculated using eqs.(3)–(10) and the water flux is calculated for each point. We then perform the matrix calculation using eq.(2) in order to find the soil moisture condition for the next stem.

Solute Movement

When the solutes are diluted in soil water, the osmotic potential should be considered in the water movement. The solution consists of various types of ions originating from organic and inorganic materials. To simplify the phenomena, the solute movement can be expressed by three types of transport, namely, advection, diffusion, and dispersion. Interactions between soil particles and solutes are not taken into account. The solute movement can be expressed by the following equation:

$$J_c = -D_h \frac{\partial C}{\partial z} + qC \tag{11}$$

where C is the concentration of the solute; J_c, the total flux of the dissolved solute; and D_h, the effective diffusion-dispassion coefficient. This coefficient is generally expressed as

$$D_h = D_s + D_p \tag{12}$$

where D_s is diffusion coefficient and D_p is known as the hydraulics dispassion coefficient. D_s is a function of the molecular diffusivity of the solute substance, soil water content, and twisted conditions of the water route. By using the above definitions, the solute movement in the soil can be expressed as

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial z}(D_h \frac{\partial C}{\partial z}) - \frac{\partial qC}{\partial z} - S_c \tag{13}$$

where S_c is the solute absorption by roots, and is given by

$$S_c = F_c S_w \tag{14}$$

where F_c is a factor of the absorption rate of the solute substance.

SPAC Model

The water movement from the soil through the plant to the atmosphere can be represented by a resistance circuit, as shown in Figure 1. In this system, soil evaporation is not taken into account to simulate the experiment described later. The switches in the soil column and atmosphere are closed when water flows in the system. The observed hydraulic resistances on no salinity condition are taken into this model.

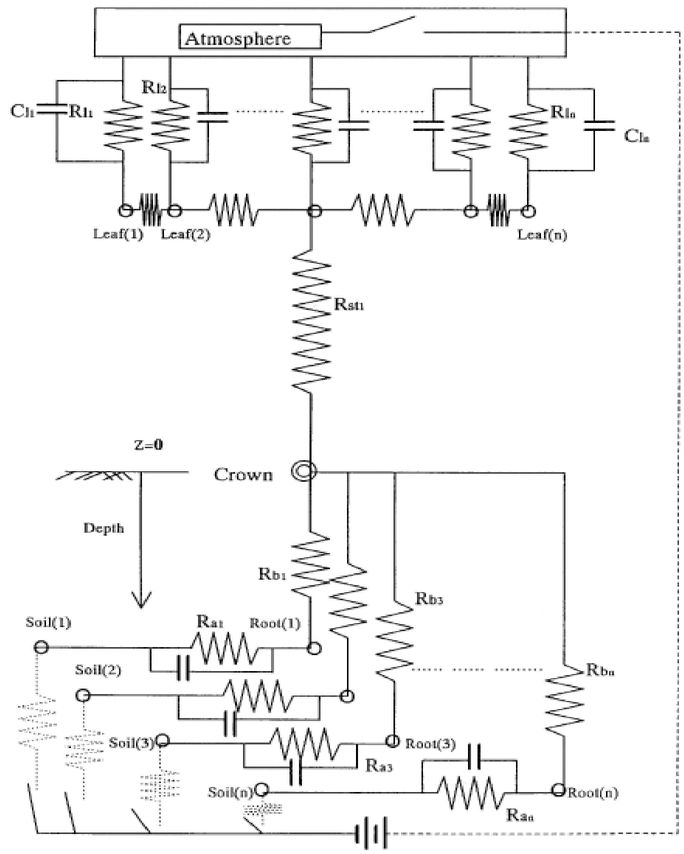


Figure1. Schematic view of SPAC model

MATERIALS AND METHODS

Plant Chamber

In order to eliminate the effects of the external environmental factors, a special chamber was used. An artificial light source (Toshiba sunlight DR4001T), air thermometer, air psychrometer, and infrared thermometer were installed in the chamber. The data obtained by these devices were transmitted to a data logger every 10 min. The pot was filled with soil to (Wagner 1/5000a) a depth of 13 cm. Several pots of broccoli were used for the experiment. Transpiration was measured every 10 min by using a weighing balance. The soil surface was covered with a plastic film to prevent evaporation. Transpiration was measured on the day before the soil moisture measurement day. The observations were started at 1000 and ended at 1800. The average temperature was 26.4º; the average relative humidity, 28.6%; and the average solar radiation, 110 W/m^2.

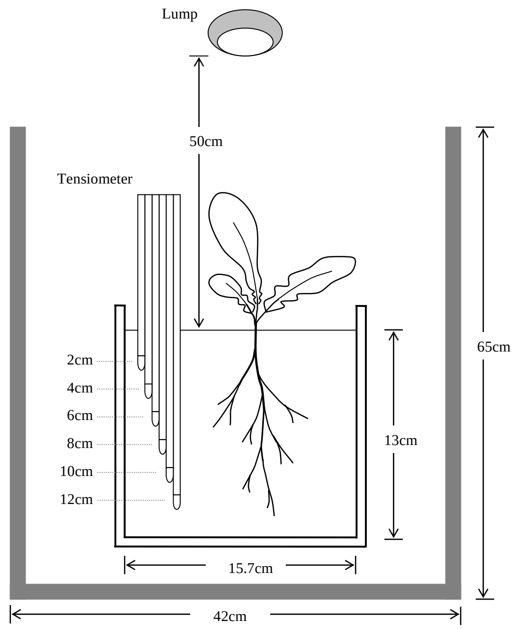


Figure 2. Plant Chamber

Soil Water Potential

The soil used in the experiment was Masa (sandy loam) and it was sieved with a mesh having a size of 5 mm. In order to remove the solute dissolved in the soil, the soil was repeatedly leached with distilled water using an aspirator. The volumetric soil moisture condition was initially set to 0.22 by spraying water over oven-dried soil. For monitoring the matric potential, six micro-tensiometers (diameter of 0.6 cm, length of 2.0 cm) were set at depths of 2, 4, 6, 8, and 12 cm. They were connected to mercury manometers. The soil characteristic curve was used to convert the matric potential into soil moisture.

Plant Water Potential

The plant water potentials were measured with a thermocouple psychrometer (Decagon SC-10) after cutting the plant body. Stem and leaf samples were obtained from several locations from the bottom to the top. Root samples were taken from depths of 2, 4, 6, 8, and 12 cm.

Solute Measurements

Before beginning the measurement, the plants were placed in distilled water and carefully planted in the soil. The concentrations of NaCl solutes were 0, 0.03, 0.05, 0.07, 0.10, and 0.15 mol/L. Solute water was sprayed on the oven-dried soil and completely mixed. The concentration 0 represents distilled water. After measuring the transpiration, the remaining salt in the soil was measured at each depth by the EC 1:5 method.

RESULTS AND DISCUSSION

Transpiration Rate

Figure 3 shows the transpiration rate for each concentration. We observed a peak of transpiration for 0.0 mol/L after 1 h and thereafter observed a constant value. The transpiration peak for 0.03 mol/L was delayed by 1 h as compared with that for 0.0 mol/L. The transpiration rate decreased with an increase in the solute concentration. When the concentration of the NaCl solution was 0.03 mol/L, the percentage reduction in the transpiration was 15.2% as compared with that in the case of distilled water. The percentage reduction at 0.05 mol/L was 43.0%, while that at 0.07 mol/L was 53.1%. These decrements adversely affected the water absorption. The percentages of transpiration were 59.7% and 63.0% at 0.10 mol/l and 0.15 mol/l, respectively. Thus, there was a larger decrease in transpiration.

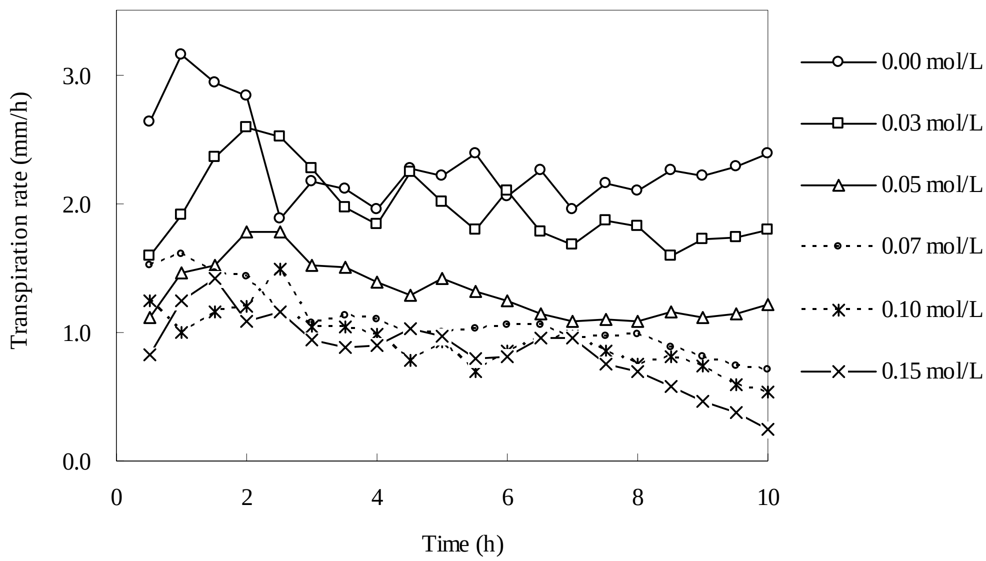
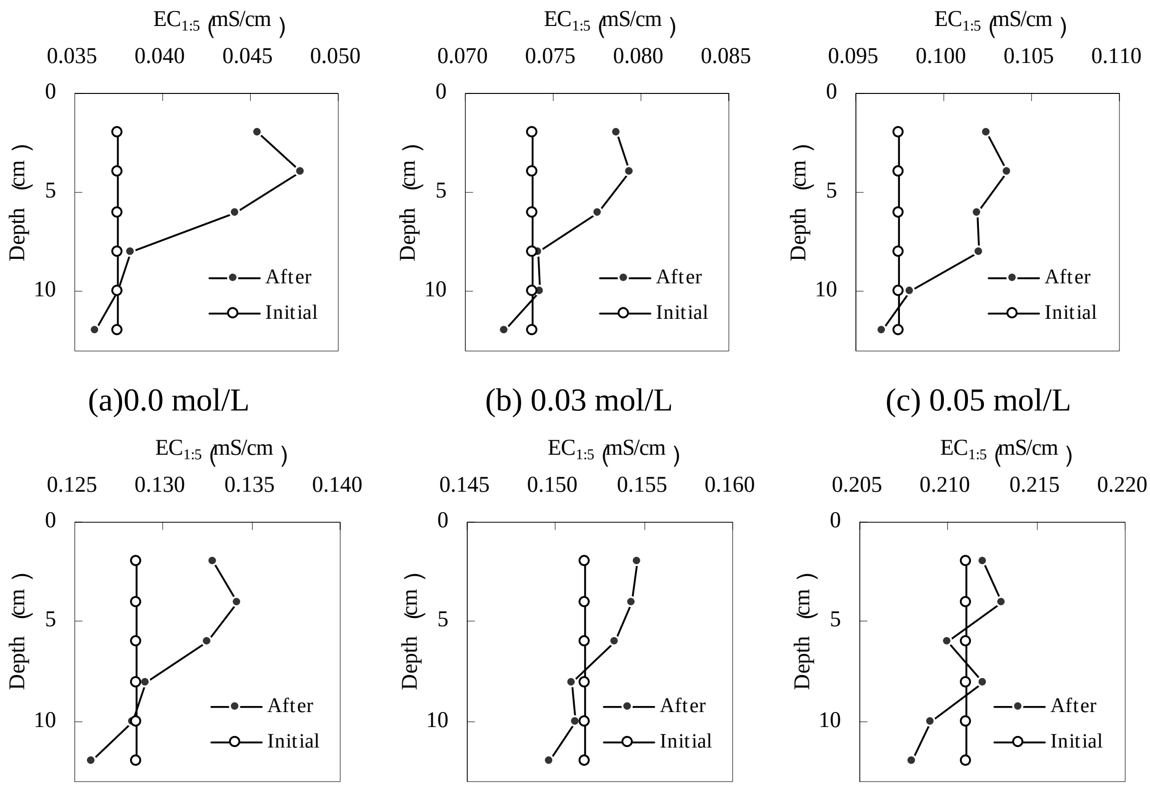


Figure 3. Transpiration rate for each salinity concentration

Soil Electrical Conductivity ($EC_{1:5}$)

Figure 4 shows the changes of EC 1:5 in the experimental pot and compares the initial EC 1:5 with that after the experiment. Each initial value was mixed each NaCl concentration with the soil equally. EC 1:5 at a depth 4 cm was larger than that at 2 cm because the root density at 4 cm was the highest and the root absorbed water. The concentration difference for each depth was small for 0.10 and 0.15 mol/L because the roots could not absorb water due to the salinity stress.



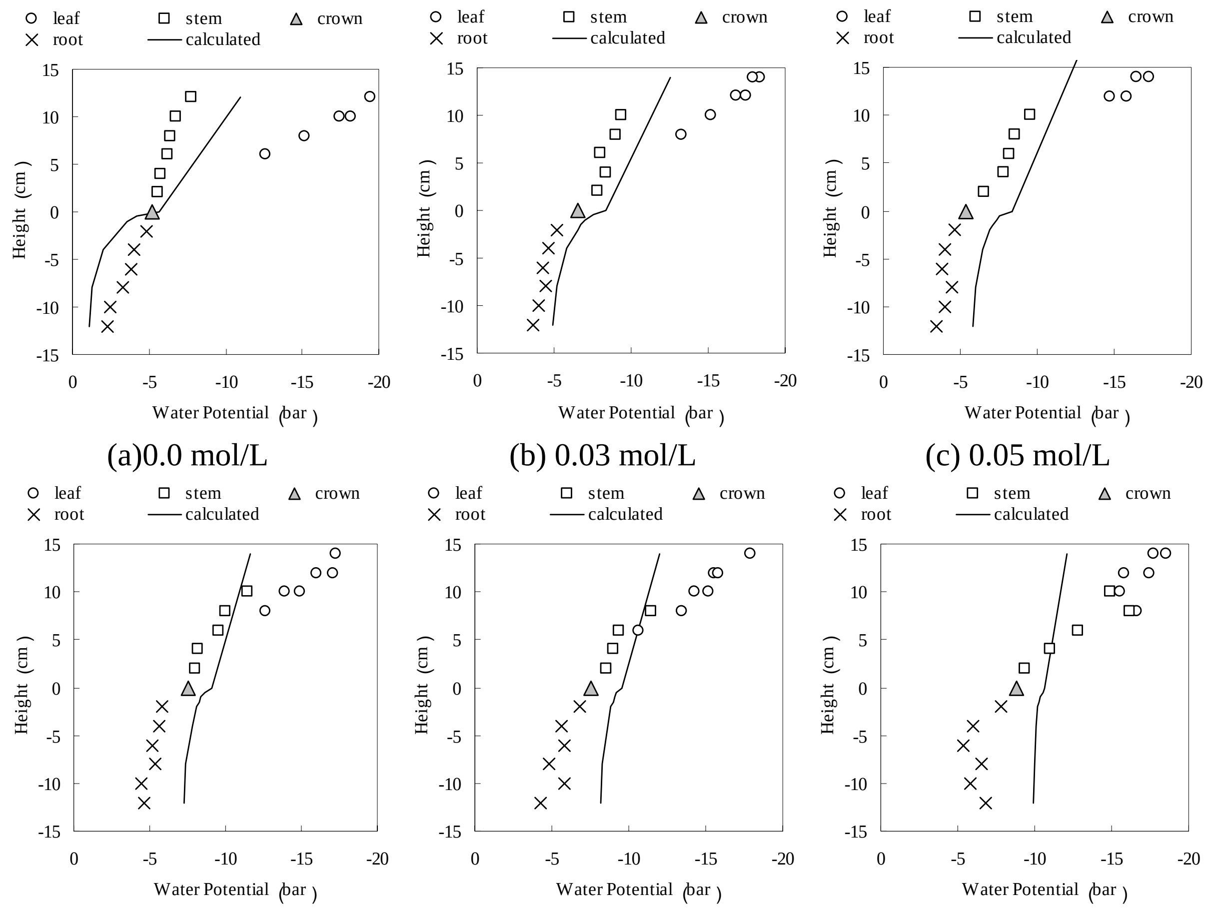
(a)0.0 mol/L (b) 0.03 mol/L (c) 0.05 mol/L

(d)0.7 mol/L (e) 0.10 mol/L (f) 0.15 mol/L

Figure 4. Changes of $EC_{1:5}$ at each salinity concentration

Accuracy of SPAC Model

Figure 5 shows the calculated results of the water potential for each point from the root to the top compared with the measured data. In the model, initial matric potential and initial salt concentrations at each salinity concentration were used. At 0.0 mol/L, the observed water potentials of the leaves, stems, and roots are shown by –20 to –12 bars, –8 to –5 bars, and –2 to –5 bars, respectively, depending on their location. The calculated line shows the average values from the tip of the leaves to the bottom of the root. Above soil surface the calculated line runs at the middle of measurement, but the root values show somewhat larger values than the observation values. The SPAC model shows a reasonable estimate of the plant water potential for 0.0 mol/L and 0.03 mol/L, however, the deviations between the results obtained by the model and the observation become larger as the solute concentration increases. The model took the osmotic potentials into account when the soil salinity changes, however, observed potentials did not match up to the calculated results because each part of hydraulic resistance on salinity condition was not taken into account. It is inferred that the potential in a leaf is maintained by confinement of a pore. It is evident that the water potential of the stem decreases with an increase in the soil salt concentration.



(a)0.0 mol/L (b) 0.03 mol/L (c) 0.05 mol/L

(d)0.7 mol/L (e) 0.10 mol/L (f) 0.15 mol/L

Figure 5. Observed and calculated water potentials for each salinity concentration

Hydraulic Resistance

Figure 6 shows the relation between the hydraulic resistance and each NaCl concentration. The hydraulic resistance increased rapidly when the soil salinity exceeded 0.10 mol/L. When the SPAC model was used on the high salinity condition, it is need to take hydraulic resistance for each part of crop into account.

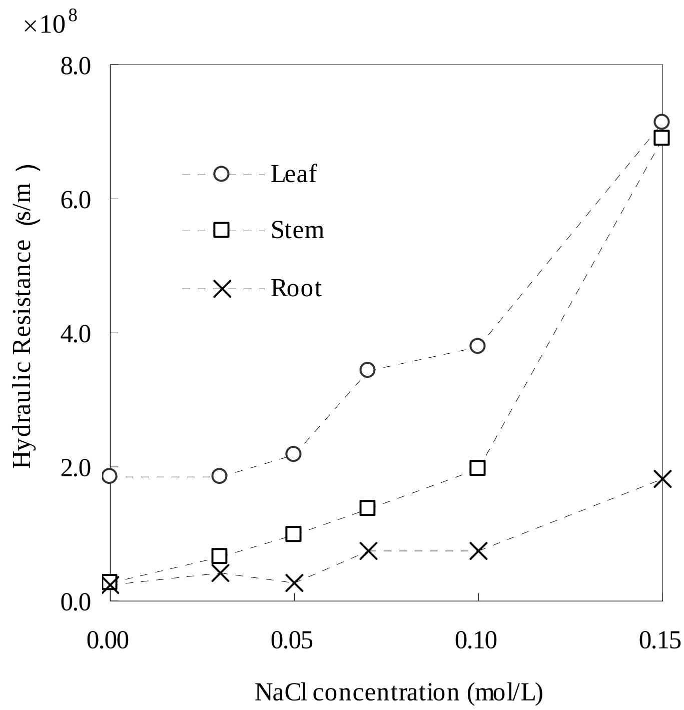


Figure 6. Hydraulic resistance for each part of the crop

SUMMARY

Salinity stress on crop often occurs when crops are grown at dry area or greenhouse, and has an influence on quantity of transpiration and crops yield greatly. The cultivation experiment about plant response to salinity stress was conducted to clarify the relationship between water consumption and hydraulic resistances by studying plants grown in soils with some different salinity concentrations. To determine the hydraulic resistance of each part of the crop, the potentials at the leaf, stem, and root were measured by using a psychrometer, and the amount of transpiration was also measured. As the concentration of the NaCl solution was 0.03 mol/L, the decrease percentage of transpiration was 15.2% compared with the case of distilled water. The decrease percentages were 43.0% and 53.1% at 0.05 mol/L and 0.07 mol/L, respectively. These decreases adversely affected water absorption. The percentages of transpiration were 59.7% and 63.0% at 0.10 mol/L and 0.15 mol/L, respectively. There was a larger decrease in transpiration. Hydraulic resistance of each crop part increased rapidly when soil salinity exceeded 0.10 mol/L. And it is clear that the disorder of absorbing water by increase of the salt concentration of the soil did not have an influence on a fall of water potential of a leaf, from results of the water potential measurement at each part of crop. It is judged that the maintenance of potential in a leaf was performed by confinement of a pore. It is clear that water potential of a stem decreased with a rise of the soil salt concentration.

REFERENCES

Amer, K. H. and J. L. Hatfield 2004: Canopy Resistance as Affected by Soil and Meteorological Factors in Potato, Agron. J., 96, pp.978-985

Boyer J.S. 1971: Resistance to water transport in soybean, bean, and sunflower, Crop Science 11, may-june, pp.403-407

Bresler E. 1973: Solute movement in soils, Ecological studies 5, Springer, pp.166-175

Cowan I.R., 1964: Tranport of water in the soil-plant-atmosphere system, J.Appl.Eco.2, pp.221-239

Gardner W. G. 1960: Dynamic aspects of water availability to plant, Soil Science 89, pp. 63-73

Hanks R.J. 1984: Prediction of crop yield and water consumption under saline conditions. Soil Salinity under irrigation, Springer, pp272-283

Hillel D. 1977: Computer simulation of soil-water dynamics, pp155-197

Hillel D., C.G.E.M. van Beek and H.Talpaz 1975: A microscopic-scale model of soil water uptake and salt movement to plant roots, Soil Science 120, pp.385-399

Landberg J.J., T.W. Blanchard and B.Warrit, 1976: Studies on the movement of water through apples trees, Journal of Experimental Botany 27 (99), pp.579-582

Longstreth, D. J. and P. S. Nobel 1979: Salinity Effects on Leaf Anatomy, Plant Physiol., 63, pp.700-703

Russo D. and G. Dagan, 1993: Water flow and solute transport in soils. Springer, pp.306

Shainberg I. and J. Shalhevet, 1984: Soil Salinity under irrigation, Springer-Verlag, p.349

INCREASING WATER AND FERTILIZER USE EFFICIENCY THROUGH RAIN GUN SPRINKLER IRRIGATION IN SUGAR CANE AGRICULTURE

P.P. Shinde[1]

ABSTRACT

Water and fertilizers are two major inputs in sugarcane productivity. The micro irrigation techniques like drip and rain gun sprinkler irrigation (RGSI) have an advantage over the surface method of irrigation to increase the water and fertilizer use efficiency. Two experiments were conducted at Vasantdada Sugar Institute, Pune during 1999 to 2006 for performance evaluation of RGSI and to optimize the dose of NPK fertilizer through RGSI for sugarcane crop. Both the experiments were conducted for one plant cane and two ratoon crops. In first experiment the performance of RGSI was studied in comparison with drip and surface irrigation. The RGSI has recorded 32 % water saving, 15 % increase in cane yield, and 1.70 times more water use efficiency as compared to surface irrigation. In second experiment the NPK fertilizer levels of 125%, 100%, 75% and 50% of recommended dose were applied through RGSI and the results were compared with 100% recommended dose of fertilizers under surface irrigation as a control. A fertilizer level of 75% has recorded 151.79 t/ha cane yield which is significantly superior to control, while 50% level has recorded 137.36 t/ha of cane yield, which is non-significant as compared to control. There was 25% NPK fertilizer saving in RGSI as compared to surface irrigation. From both the studies it is concluded that the rain gun sprinkler irrigation was effective in sugarcane crop for 32 % water saving, 25% NPK fertilizer saving, 15 % increase in cane yield, and 1.70 times more water use efficiency as compared to surface irrigation.

INTRODUCTION

Sugarcane is the most important cash crop of India occupying about two per cent cultivable area. The sustained sugarcane production depends upon efficient water management throughout the crop growth period. Large variations in cane yields are noticed in the country from year to year and place to place due to many production constraints. Timely availability of irrigation as per the need of the crop is one of the serious constraint among these. The cultivators are adopting drip and rain gun sprinkler irrigation (RGSI) techniques in sugarcane crop for increasing water and fertilizer use efficiencies. The sprinkler irrigation is an accepted method of irrigation not only in developed countries but also in the developing countries. Due to high initial investment of this system, the adoption is very slow. More than 10 M ha area is under sprinkler irrigation in the world (Sivanappan, 1998). In India there is a increasing trend for adoption of RGSI in sugarcane crop. The fertigation through micro irrigation systems is also gaining a momentum in the country, as this technique has advantage of application of fertilizers at appropriate rate and in desired concentration. This technique also provides flexibility of fertilization, which enables specific requirements of the crops to be met at different stages of its growth (Shinde *et al.* 2005).

The fertilizer losses such as leaching, volatilization and dentrification are avoided and there is a

[1] Scientist-Irrigation Water Management; Vasantdada Sugar Institute, Pune, India; pps_irrigation@rediffmail.com / pps2007@yahoo.com

improvement in fertilizer use efficiency. Looking to the importance of RGSI and fertigation technology in sugarcane agriculture, the present study was under taken.

MATERIALS AND METHODS

Experiment No. 1

With a view to evaluate the performance of Rain gun sprinkler irrigation in sugarcane crop, an experiment with sugarcane variety Co 86032 was conducted at Vasantdada Sugar Institute, Pune during 1999 to 2002 for one plant cane and two ratoon crops. The treatments were as follows

T1- Rain gun sprinkler irrigation.
T2- Drip irrigation.
T3- Surface irrigation (Control).

The paired row sugarcane planting with row spacing of 0.75 x 1.50 m was used in drip and sprinkler irrigation while 1.0 x 1.0 m sugarcane planting was used in surface irrigation. The standard recommended practices of cultivation were followed throughout crop growth period.

Experiment No. 2

With a view to optimize the dose of NPK fertilizers through rain gun sprinkler irrigation for sugarcane an experiment with sugarcane variety Co 86032 was conducted at Vasantdada Sugar Institute, Pune during 2003 to 2006 for one plant and two ratoon crops in complete randomized design with four replications. The fertilizer levels were varied as as per the following treatment details as compared to 315 kg N, 140 Kg P2O5 and 140 kg K2O per ha of recommended dose.

T1-125% of recommended dose of NPK through RGSI.
T2-100% of recommended dose of NPK through RGSI.
T3 - 75 % of recommended dose of NPK through RGSI.
T4- 50% of recommended dose of NPK through RGSI.
T5 - 100% recommended dose of NPK under surface irrigation (Control).

The wider spaced sugar cane planting of 1.2 m was used for the experimentation. The NPK fertilizers were applied in the form of Urea, Diammonium phosphate and Muriate of potash. In rain gun sprinkler irrigation fertilizers were applied in four equal splits up to 4.5 months of crop age while in surface irrigation it was applied by hand application as per recommended splits. The specifications of RGSI were as follows

- Make: Premier Irrigation
- Model no.: ZNO 23 LOPS W part Circle Single Nozzle.
- Operating Pressure range: 2.8 to 3.8 Kg per sq. cm.
- Diameter of spray: 53 to 62 m.
- Discharge: 280 to 310 liters per minute.

RESULTS AND DISCUSSION

Sugarcane Yield

The cane yield of 118.5 t/ha was obtained in drip irrigation followed by 117.2 t/ha in RGSI. The surface irrigation has recorded 101.6 t/ha of cane yield (Table 1). The increase in cane yield in drip irrigation was 16.6 % while in RGSI it was 15.3 % as compared to surface irrigation.

Water aving and Water Use Efficiency

The total quantity of water applied in RGSI and drip irrigation was 1744 and 1312 mm respectively while in surface irrigation it was 2565 mm (Table1). There was water saving of 32.0 % in RGSI while 48.8 % in drip irrigation as compared to surface irrigation. The water use efficiency in RGSI and drip irrigation was 0.0672 and 0.0903 t/ha/mm respectively as against 0.0396 t/ha/mm in surface irrigation. The RGSI has recorded 1.7 times more water use efficiency as compared to surface irrigation.

Table 1. Quantity of Water Applied , Cane Yield and Water Use Efficiency
(Pooled data of one plant and two ratoon crops)

Treatment	Particulars of treatment	Quantity of water applied, mm	Cane yield, t/ha	Water use efficiency, t/ha/mm
T1	Rain gun sprinkler irrigation	1744	117.2	0.0672
T2	Drip irrigation	1312	118.5	0.0903
T3	Surface irrigation	2565	101.6	0.0396

Uniformity of Water Distribution

The uniformity of water distribution in RGSI was 75.89% while in drip irrigation it was 93.29 %. The drip irrigation was found more effective in uniform distribution of water as compared to RGSI.

Fertilizer Saving

The cane yield obtained in fertilizer levels of 125%, 100% and 75% of recommended dose of NPK through RGSI was significantly superior over control. A fertilizer level of 75% of recommended dose through RGSI has recorded 151.79 t/ha of cane yield, which is 14.80 % more as compared to control. Reducing the dose to 50% has recorded 137.30 t/ha of cane yield, which is non-significant as compared to control (Table 2). This indicates that 25% NPK fertilizers can be saved if applied through RGSI for sugarcane. These results are in conformity with those reported by Aiyanna, *et al.* (2001).

Table 2. Effect of NPK Fertilizer Levels on Cane Yield
(Pooled data of one plant and two ratoon crops)

Treatment	**NPK fertilizer levels**	**Cane yield t/ha**
T1	125% of recommended dose through RGSI	156.05*
T2	100% of recommended dose through RGSI	154.09*
T3	75% of recommended dose through RGSI	151.79*
T4	50% of recommended dose through RGSI	137.30
T5	100% recommended dose under surface irrigation (Control)	132.21
SE ±		2.47
CD at 5%		7.46

* Significantly superior over control

CONCLUSION

The data obtained in these studies shows that Rain gun sprinkler irrigation was found effective in sugarcane crop for saving of irrigation water by 32%, saving of NPK fertilizer by 25%, increase in cane yield by 15% and 1.7 times more water use efficiency compared to surface irrigation.

REFERENCES

Aiyanna, B. Sabina, Farooqi, A.A., Khan, M.M. and Vasundhara, M. (2001) Effect of sprinkler fertigation with normal and water soluble NPK fertilizers on nutrient uptake and yield of geranium. Proceedings of International conference on micro and sprinkler irrigation held at Jalgaon, Maharashtra, India pp. 489-493.

Jhoty S. Ramasamy and P. K. Tulloo (2001). A survey of irrigation practices for sugarcane in Mauritius. Proceedings of the 24th ISSCT Congress held at Brisbane, Australia, Vol. II pp. 288-291.

Kulkarni S. A. (1998) Status and scope of sprinkler irrigation in Maharashtra. Proceedings of Workshop on Micro irrigation and sprinkler irrigation system held at N. Delhi, India pp. I 22 - 27.

Shinde,S.H., Deshpande,A.B and Atre,A.A. (2005) Fertigation in sugarcane. Proceedings of national seminar on Relevance of micro irrigation for sugarcane held at Vasantdada Sugar Institute, Pune, India pp. 140-153.

Sivanppan R. K. (1998) Status, Scope and Prospects of sprinkler irrigation in India. Proceedings of Workshop on Micro irrigation and sprinkler irrigation system held at N. Delhi, India pp. I 17 - 21.

Soopramanien G.C.(1999). Sugarcane Irrigation- A Review. Proceedings of the 23rd ISSCT Congress held at New Delhi, India, Agriculture Program pp. 1-7.

TESTING AND EVALUATION OF INEXPENSIVE HORIZONTAL-AXIS MECHANICAL CURRENT METERS

Kirk Thibodeaux, P.E.[1]

ABSTRACT

In recent years the U.S. Geological Survey (USGS) has been receiving requests for information on the performance of inexpensive horizontal-axis mechanical current meters. The USGS has conducted tests on some of the equipment described in this paper over 15 years ago; but, changes and improvements to these meters prompted their retesting and evaluation. Using the same procedures as used to test and evaluate USGS standard Price type AA and pygmy meters in the USGS's Hydraulic Laboratory's NIST traceable towing tank and tilting flume facilities, two types of inexpensive horizontal-axis mechanical current meters and a 2-dimensional field use acoustic Doppler velocimeter (2-D ADV) were tested to determine how well they performed in relation to the manufacturer's specification and how well they performed after individual calibrations. Data are presented showing the equipment's performance characteristics as compared to the manufacturer's specifications and USGS standard mechanical current meters. Results presented show that the inexpensive horizontal-axis mechanical current meters did not meet their stated accuracy specifications while the 2-D ADV and the standard USGS meters did meet their stated accuracy specifications.

INTRODUCTION

The USGS continues to receive requests for information on the performance of relatively inexpensive horizontal-axis mechanical current meters (under $2500), specifically the Flow Probe from Global Water Instrumentation[2] and the Swoffer Instruments model 2100 meters. Additionally, requests for information on the SonTek/YSI FlowTracker have been on the increase. Some previous testing was done on the Swoffer meters by the USGS [Fulford 2001] but not on the Flow Probes.

The object of this paper is to outline the results of two sets of tests conducted on relatively inexpensive mechanical current meters and to compare the results to the USGS standard meters, the Price type AA and pygmy meters, as well to the FlowTracker. Tow tank testing was used to determine each meter's ability to register true velocity of a steady velocity over a range of velocities. Tilting flume testing was used for testing individual meter's repeatability and response to oblique, or angled, flows (cosine response).

EQUIPMENT TESTED

The equipment tested (Figure 1) consisted of horizontal-axis meters from Global Water Instrumentation and Swoffer Instruments, a SonTek/YSI FlowTracker handheld 2-D ADV

[1] Manager - U.S. Geological Survey Hydraulic Laboratory; Building 2101; Stennis Space Center, MS 39529; kgthibod@usgs.gov

[2] Use of trade, product, or firm names is for descriptive purposes and does not imply endorsement by the U.S. Government.

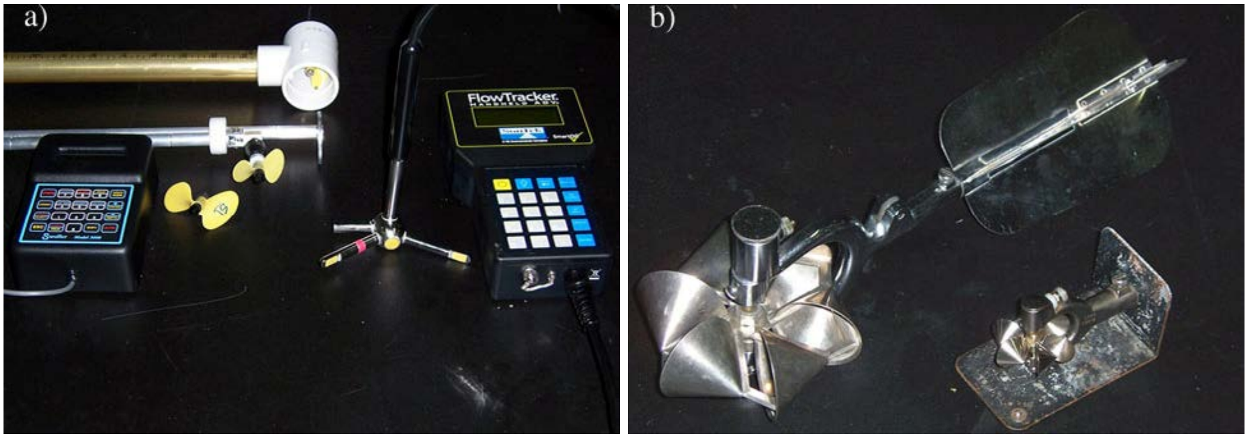


Figure 1. Current meters tested. a) From top clockwise; Global Water Flow Probe FP101, SonTek/YSI FlowTracker 2D handheld ADV, Swoffer 3 inch prop, and Swoffer 2 inch prop. b) USGS Price type AA (left) and pygmy.

(Acoustic Doppler Velocimeter) to test the state of the art in point velocity measurement, and USGS standard Price type AA and pygmy meters for reference to earlier work. A summary of each meter's stated performance characteristics is also given in Table 1.

The Global Water Instrumentation meters were three of the model FP101 Flow Probes, serial numbers 45610, 45611, and 45613. The Flow Probe has a stated velocity range of 0.3 to 15 feet per second (ft/s) and accuracy of ±0.1 ft/s [Global Water Instrumentation 2007]. These meters were purchased by the USGS for testing.

The Swoffer meters were two each of model 2100 with 2 and 3 inch props (propellers). All tests conducted, with the exception of 2, were conducted with the model 3000 indicator (serial number 006883). The remaining 2 tests were conducted with a model 2100 indicator (serial number 4650). The Swoffer meters with both indicators have a stated velocity range of 0.1 to 25 ft/s and accuracy of ±1 percent with "periodic user required calibration tests and adjustments" [Swoffer

Table 1. Meter specifications (based on manufacturer's published data)

Meter Type	Velocity Range (ft/s)	Accuracy (in percent of velocity) Velocity in ft/s					
		0.25	0.50	0.75	1.1	1.5	2.2
AA	0.1 - > 20	± 6.0	± 3.4	± 2.5	± 2.0	± 1.5	± 1.5
Pygmy	0.2 – 3	± 6.0	± 3.4	± 2.5	± 2.0	± 2.0	± 2.0
Global Flow Probe	0.3 – 15	± 33.3	± 20.0	± 13.3	± 9.1	± 6.7	± 4.5
Swoffer	0.1 – 25	± 1	± 1	± 1	± 1	± 1	± 1
FlowTracker	0.003 – 13	± 3.3	± 1.6	± 1.1	± 1	± 1	± 1

Instruments 2007]. The 2 inch props and the two indicators were purchased by the USGS for testing. The 3 inch props were loaned to the USGS by the Streamkeepers of Clallam County of Port Angeles, Washington.

The SonTek/YSI FlowTracker, serial number P1515, is a 2-D unit and was randomly selected from the USGS Hydrologic Instrumentation Facility's warehouse stores. The FlowTracker has a stated velocity measuring range of 0.003 to 13 ft/s and accuracy of ± 1 percent of the reading or ±0.0082 ft/s (±0.25 cm/s); whichever is greater [SonTek/YSI 2007].

The standard USGS Price meters were two meters randomly selected from a group of meters exchanged at a USGS surface-water review of the USGS Hawaii Water Science Center. The AA, serial number A99053, and pygmy, serial number P97080, meters were used in "rebuilt" condition. The velocity range for pygmy meters using the standard rating is 0.2 to 3 ft/s and the AA meter is 0.1 to greater than 20 ft/s [Fulford 2001]. The stated accuracies for USGS standard rating for AA and pygmy meters are dependent on velocity and range from ±6 percent at 0.25 ft/s for both meters to ±2 percent at 1.5 ft/s and higher for pygmy meters and to ±1.5 percent at 1.5 ft/s and higher for AA meters [Hubbard, et al 2001].

TEST SETUPS

Tow Tank Facility

All meters were tow-tank tested to see how well each meter worked in relation to the reference speed of the tow carriage. The tow tank was also used to determine the Prop Pitch, field calibration values, for all of the Swoffer props. The tow tank is a 12 ft by 12 ft by 450 ft long tank with a carriage that travels on rails mounted to the top face of the tank's side walls (Figure 2). The carriage can travel at velocities ranging from 0.03 to 18 ft/s. Constant water velocity is simulated by suspending the meter being tested from the tow carriage into the still water of the tow tank and moving the carriage at a constant velocity. The accuracy limit for any run velocity as computed from the time and distance measured by the data acquisition system on the tow carriage is: $V_{Limit} = V_{Measured} \pm 0.001\ V_{Measured}$. The accuracy limit of the tow carriage's timers were within ± 0.01 percent of the referenced time and the calibrated distance was found to be within ± 0.01 percent of the established length of 200.00 ft during their calibrations over the test period. All timer and reference distance calibrations are traceable to the National Institute of Standards and Technology (NIST).

Each meter was towed at the USGS standard calibration speeds of 0.25, 0.50, 0.75, 1.1, 1.5, 2.2, 3, 5, and 8 ft/s. These points are a combination of the Price type AA and pygmy standard calibration speeds. The meters were towed twice at each speed, once traveling in the forward direction (north) and once in the reverse direction of travel in the same section of tank. The meters were always facing into the direction of simulated flow. The reference speed of the tow carriage was calculated using the carriage data system to collect distance traveled and time.

All meters, with the exception of the USGS standard meters, were manually recorded. The USGS meters were connected to the carriage's data system and the meter's pulse information was collected with the carriage data acquisition system.

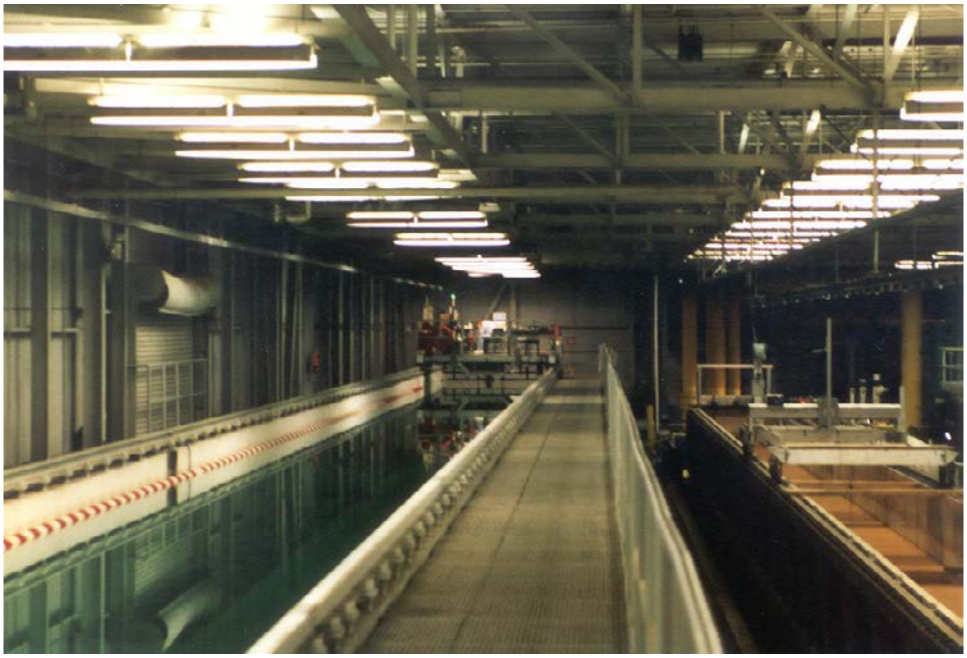


Figure 2. USGS tow tank and tow carriage

Global Flow Probe Each Flow Probe was attached to the custom mount on the south end of the tow carriage (Figure 3) and towed using the standard USGS tow speeds. However, because the Flow Probe's minimum velocity is stated to be 0.3 ft/s, an additional data point of 0.30 ft/s was added to the tow schedule. The data collected from each meter included readings of its average velocity and instantaneous velocity at the 40 second tow time, 20 seconds at 8 ft/s.

Swoffer Meters The Swoffer meters were mounted to an existing meter mount on the north end of the tow carriage using adaptors purchased from Swoffer and modified to fit the carriage mount. Meter data were collected manually and consisted of meter counts/revolutions and time from the Model 3000 interface, and meter counts from the Model 2100 interface. Time for the Model 2100 interface meters was obtained from the tow carriage's data system. Data were collected over tow times of 40 seconds, 20 seconds at 8 ft/s.

To determine the Prop Pitch for the four props, each prop was towed 10 times at 1 ft/s for 20 ft in the tow tank. Using the Model 3000 indicator in its "Auto Entry" mode, each prop's field calibration Prop Pitch was obtained.

SonTek/YSI FlowTracker The SonTek/YSI FlowTracker meter was mounted to the existing meter mount on the north end of the tow carriage. After seeding the tank with hydrated lime to get an adequate level of back scattering material (SNR levels above 10 dB), meter data were collected manually for each velocity run. The data were also recorded by the FlowTracker and later downloaded for additional analysis. All data collection times were 40 seconds for the FlowTracker.

Figure 3. Flow Probe testing in tow tank

Price Type AA and Pygmy Meters The AA and pygmy meters were attached to the existing meter mount on the north end of the tow carriage (Figure 4) and data were collected using the carriage's data collection system. Data collected included meter pulse counts (revolutions), time, and distance traveled. Data collection times vary for each velocity and were dependant on the standard calibration minimum meter revolution requirement.

Tilting Flume Facility

All angle response and repeatability testing was conducted in the tilting flume facility. The tilting flume (Figure 5) is a 6 ft wide, 3 ft deep and 250 ft long flume that can be tilted to a slope of 1 percent. The discharge capacity is at least 50 cubic feet per second (cfs) supplied by the laboratory's constant head tank. The head box to the flume is 6 x 3 x 30 ft and serves to straighten the flow prior to introduction to the flume. For the angle response and repeatability testing, the flume was set with a discharge to deliver a velocity of approximately 2 ft/s at 2.5 ft deep.

To test the cosine response at angular flows, each meter was rotated in 10 degree increments through angles ranging from -90 degrees to +90 degrees (negative angles for horizontal-angle testing are turning the meter in a counter-clockwise direction). The horizontal-axis meters, Flow Probe and Swoffer meters, which are symmetric about their centers of rotation, were rotated only in the horizontal plain. The vertical-axis meters, AA and pygmy, and the FlowTracker were rotated in both the horizontal and vertical plain (negative vertical angles are defined as the flow approaching the meter from the bottom of the meter).

Figure 4. Meter mount on tow cart

Figure 5. USGS tilting flume facility

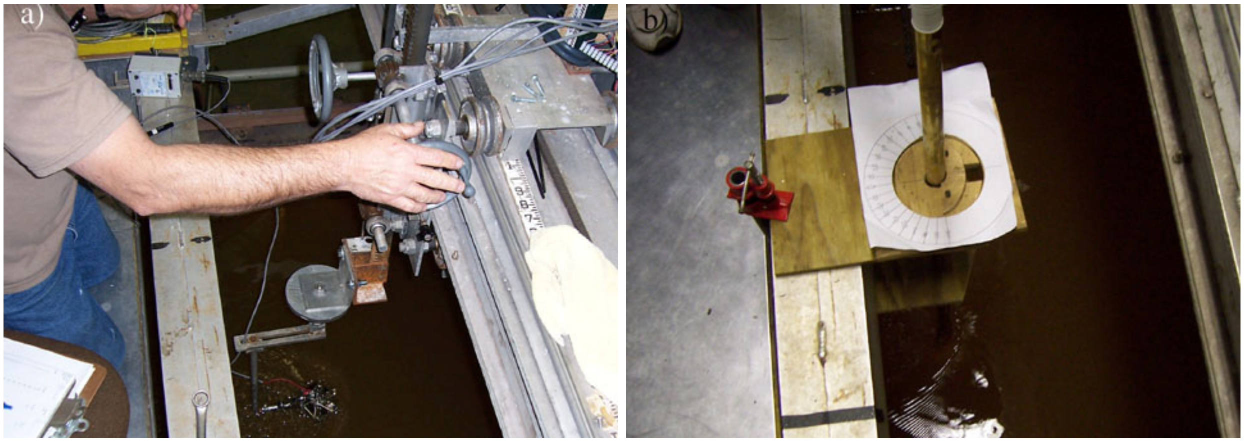


Figure 6. Tilting Flume angle test mounts. a) For all meters except Flow Probe. b) Flow Probe test mount.

The repeatability testing consisted of collecting velocity data for ten discrete velocity measurements, 40 seconds each.

Each meter was set such that the center of its measuring section remained in the same point as the meter was rotated. All meters, with the exception of the Flow Probes, were attached to a custom fabricated offset mount to achieve this (Figure 6a). The Flow Probes, which have their impeller directly below the handle, were set in a mount that allowed them to be rotated (Figure 6b).

After the flow in the flume was set and stabilized, each meter was mounted in its normal operating orientation and ten 40-second velocity samples were collected for the repeatability portion of the testing and as a reference velocity for the cosine response testing. The meters were then rotated to each test angle and one 40-second velocity reading was collected for each angle turned.

To test the vertical-axis meters to vertical-angled flow, these meters were tipped onto their sides for data collection. As with the horizontal-angle testing, ten 40-second velocity samples were taken with the meter pointed directly into the flow and one 40-second reading at each angle turned.

RESULTS

The testing results are presented in the following tables and graphs.

Tow Tank Testing

Global Flow Probe The three Flow Probes were tested over two days at the speeds listed in the test setup section. Errors in the readings from the Flow Probes tested ranged from -20.9 percent at 8 ft/s for meter 45611 to 13.3 percent at 3 ft/s for meter 45613 (see Table 2). Figure 7 shows that, even with the widest accuracy range of the meters tested (see Table 1), each Flow Probe meter fell outside of its accuracy limits for at least 4 of the 9 velocities tested.

Table 2. Mean error in percent for tow tank testing of Flow Probe and Swoffer meters

	Error (in percent of reference velocity)						
Nominal Tow Speed (fps)	FP 45610	FP 45611	FP 45613	Swoffer 2" #1	Swoffer 2" #2	Swoffer 3" #2	Swoffer 3" #12
0.25	-14.6	-14.6	-19.5	-40.6	-23.7	-14.0	-14.2
0.50	-0.8	-1.8	-10.7	-10.5	-6.7	-4.9	-3.7
0.75	1.8	1.8	7.9	-4.0	-2.4	-3.0	-2.1
1.1	4.5	5.9	9.1	-1.0	0.0	-2.0	-1.1
1.5	6.8	6.8	-0.4	0.3	1.0	-1.2	0.0
2.2	8.6	7.4	11.4	1.6	2.0	-0.8	-0.1
3.0	9.4	-2.0	13.3	2.3	2.7	-0.5	0.2
5.0	6.0	7.9	-1.1	2.9	3.3	-0.8	-0.2
8.0	10.5	-20.9	-4.0	3.1	2.9	-1.7	-1.0

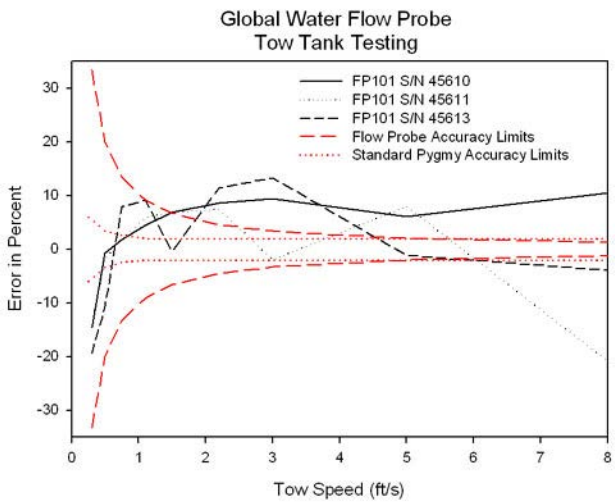


Figure 7. Flow Probe tow tank test results

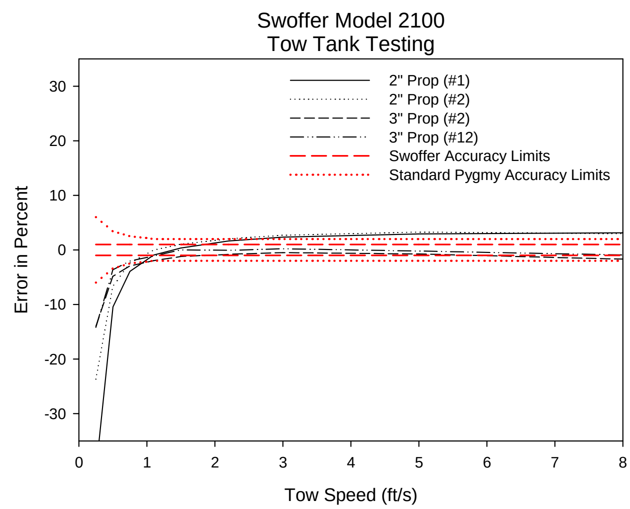


Figure 8. Swoffer meter tow tank test results

Table 3. Swoffer meter field calibration Prop Pitch

Prop	Pitch
2" #1	175.53
2" #2	177.95
3" #2	133.30
3" #12	133.19

Swoffer Meters The four Swoffer meter props tested were tested over a three day period: two days for testing at the above listed velocities, and one day to determine each prop's field Prop Pitch (Table 3). Errors in the readings from the Swoffer meters using the field determined Prop Pitches ranged from -40.6 percent at 0.25 ft/s to 3.3 percent at 5 ft/s for the 2 inch props and from -14.2 percent at 0.25 ft/s to 0.2 percent at 3 ft/s for the 3 inch props (see Table 2). Figure 8 shows that all Swoffer props tested using their field determined Prop Pitches fell outside of their stated accuracy limits, the most stringent of all the meters tested, for most of the velocities. The meters also fell outside of the USGS accuracy limits.

The Prop Pitches obtained in the tow tank averaged 176.74 for the 2 inch props and 133.25 for the 3 inch props. This compares to the Swoffer default pitches of 186 for the 2 inch prop and 130 for the 3 inch prop. [Swoffer 2002]

SonTek/YSI FlowTracker The FlowTracker was tested during one day at all velocities listed. Errors in the readings from the FlowTracker ranged from -0.6 percent at several velocities to 0.2 percent at 2.2 ft/s (Table 4). Figure 9 shows that the FlowTracker was within its stated accuracy limits for all velocities tested.

Price Type AA and Pygmy Meters The Price Type AA and pygmy meters were tested during one day at all velocities listed. Errors ranged from -0.9 percent at 0.25 ft/s to 0.7 percent at 0.75 ft/s for the AA meter and from -0.7 percent at 1.1 ft/s to 3.4 percent at 0.25 ft/s for the pygmy meter (Table 4). Figure 9 shows that both meters were within the USGS Standard accuracy limits for the AA meter, the more stringent of the AA and pygmy limits, for all velocities tested.

Tilting Flume Facility

Angle (Cosine Response) Testing Results for the angle testing are given in Tables 5, 6, and 7 and Figures 10 and 11.

In general, the horizontal-axis meters under registered the correct cosine component of the velocity when the meter was turned in the flow. The Flow Probes were inconsistent from meter to meter in their response. As seen in Table 5 and Figure 10, one of the three meters (45611) over registered the velocity when the meter was turned in a positive angle direction. The Swoffer meters were consistent in their performance, registering low for almost all angles turned.

For both the Flow Probes and the Swoffer meters the registration errors were less than 10 percent for flow angles of ±20 degrees, with the Swoffers working slightly better with registration errors less than 10 percent for angles of ±30 degrees.

The vertical-axis mechanical meters, the AA and pygmy meters, performed as expected and consistent with previously published data [Fulford, et al 1993 and Fulford, et al 1994]. In flow angles in the horizontal direction, both AA and pygmy meter registration errors were less than 10 percent for angles ±20 degrees. As with previous studies, horizontal angles always produce an over registration in the velocity readings because these meters, by their design, measure the magnitude of the flow. In the vertical angle flow directions, the AA registered within 10 percent for angles of ±40 degrees, while for the pygmy meter, it was +30 to -10 degrees. The better response of the AA and pygmy meters to vertical angles is due to the fact that in vertical angle situations the flow is hitting the rotors in a manner similar to the horizontal-axis meters. The larger errors for the pygmy meter are due to the meter's relatively large yoke.

The FlowTracker was much better at resolving flow angles. As seen in Tables 6 and 7, the FlowTracker's readings were always within ±10 percent for angles of ±60 degrees in the horizontal and vertical.

Table 4. Mean error in percent for tow tank testing of FlowTracker, Price AA and pygmy meters

	Error (in percent of reference velocity)		
Nominal Tow Speed (fps)	FT P1515	AA A99053	Pygmy P97080
0.25	-0.6	-0.9	3.4
0.50	-0.6	0.0	-0.1
0.75	-0.5	0.7	-0.6
1.1	0.1	0.4	-0.7
1.5	-0.5	0.4	0.0
2.2	0.2	0.4	0.2
3.0	0.1	0.6	0.0
5.0	-0.6	0.3	0.3
8.0	-0.3	0.0	0.0

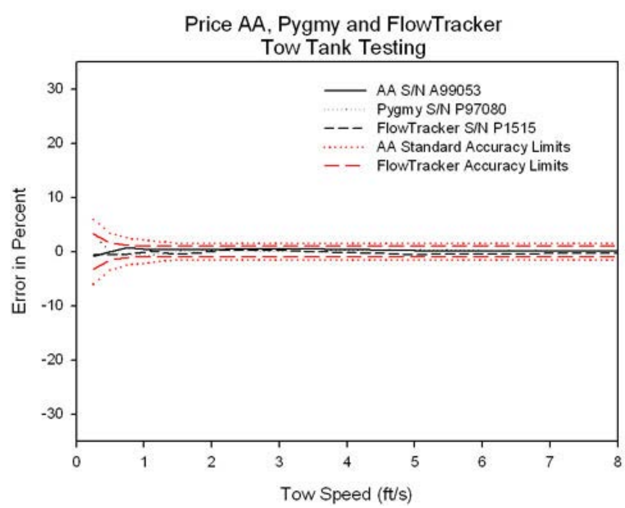


Figure 9. Price AA, pygmy, and FlowTracker tow tank test results

Table 5. Error in percent of meter reading for horizontal angles turned for Flow Probe and Swoffer meters

	Error (in percent)						
Angle Turned (deg.)	FP 45610	FP 45611	FP 45613	Swoffer 2" #1	Swoffer 2" #2	Swoffer 3" #2	Swoffer 3" #12
80	--	13.8	--	--	--	--	--
70	-43.2	15.6	-57.9	--	--	--	--
60	-27.7	13.2	-22.9	-45.0	-42.2	-36.0	-35.6
50	-15.2	20.5	-4.1	-29.1	-26.4	-32.1	-32.4
40	-2.1	17.2	10.0	-17.3	-13.2	-19.2	-20.1
30	5.3	14.1	10.4	-8.2	-4.4	-7.4	-7.8
20	6.2	8.0	8.8	-2.1	-1.2	-2.5	-2.8
10	1.9	3.6	1.8	-1.1	-0.2	0.0	0.7
0	0.9	-0.6	-4.4	-1.3	1.0	-0.2	-0.3
-10	0.3	-1.3	0.2	0.4	0.1	-0.2	0.8
-20	-0.6	-3.9	0.1	-1.4	-1.9	-2.3	-1.5
-30	-2.8	-9.3	-2.1	-4.2	-2.2	-6.5	-6.5
-40	-11.2	-19.8	-10.1	-11.3	-9.8	-16.5	-14.6
-50	-15.2	-21.9	-20.9	-19.3	-23.1	-30.7	-29.8
-60	-20.1	-20.9	-33.2	-39.8	-40.6	-36.2	-34.5
-70	-47.9	-54.7	--	--	--	--	--
-80	--	--	--	--	--	--	--

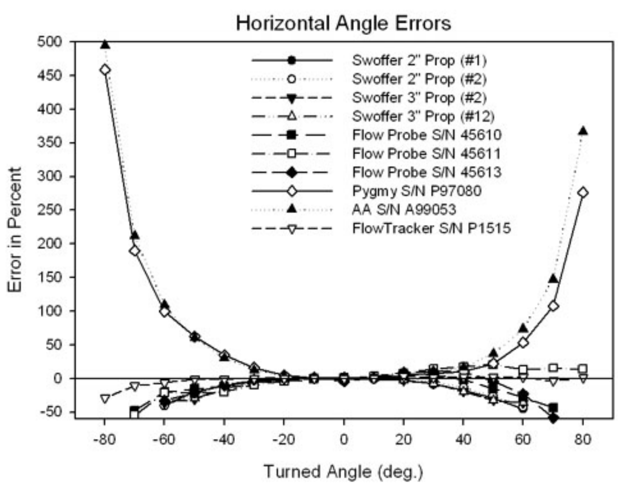


Figure 10. Horizontal angle errors

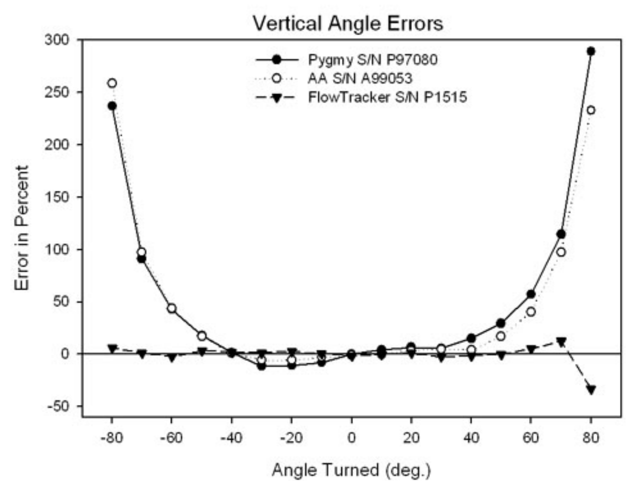


Figure 11. Vertical angle errors

Table 6. Error in percent of meter reading for horizontal angles turned for FlowTracker, Price AA and pygmy meters

	Error (in percent)		
Angle Turned (deg.)	FT P1515	AA A99053	Pygmy P97080
80	-32.9	366.5	276.4
70	12.6	147.1	107.5
60	5.2	73.6	53.0
50	0.2	36.8	22.5
40	-1.4	16.8	10.5
30	-2.4	9.5	6.7
20	1.1	5.1	4.8
10	-0.1	1.5	0.0
0	-1.3	0.9	1.0
-10	0.7	-0.2	1.2
-20	2.7	3.0	4.5
-30	1.5	12.3	15.9
-40	2.2	29.8	34.8
-50	3.3	60.1	62.3
-60	-2.1	109.1	99.8
-70	1.3	211.9	189.7
-80	6.3	493.9	458.4

Repeatability The repeatability results of ten 40 second velocity readings are given in Table 8. The results are given as a percentage of the mean flow reading of each meter and are the 2σ value range. With the exception of the Flow Probe 45611, the 2σ value for all the meters was better than 2.5 percent, with 45611 coming in at 3.1 percent. These values are not quite what were expected. From previous studies [Fulford 2001] the vertical-axis meters should have had a 2σ value of approximately one half of the horizontal-axis meters. The difference in test setup, tow tank for Fulford and tilting flume for the testing presented here, are most likely the reason for this discrepancy and warrants further investigation.

CONCLUSIONS

Tow tank testing of the relatively inexpensive horizontal-axis mechanical meters showed that the meters do not perform as expected from their listed accuracies. The Swoffer meter's accuracy limits appear to be too tight for the meter being used with field calibrations, while the Global Water's Flow Probes, even with its large accuracy limits at low velocities, consistently falls out of its accuracy limits. The vertical-axis meters, the Price type AA and pygmy, and the

FlowTracker do perform as advertised by registering the flow within their respective accuracy limits.

Horizontal-angle test results indicated that all of the meters tested will register the flow within ±10 percent within angles of ±20 degrees. The FlowTracker, being a 2-D meter, was, as expected, the best performing meter in resolving horizontal angled flow.

Vertical-angle test results indicated that the AA meter will register the flow within ±10 percent within angles of ±40 degrees. The pygmy meter, however, will register the flow within ±10 percent within angles of ±10 degrees due to its relatively large yoke interfering with vertical flows. The FlowTracker will register the flow within ±10 percent within angles of ±60 degrees.

The repeatability testing indicated that all but one of the meters, Flow Probe S/N 45611, had 2σ values of better than 2.5 percent.

Table 7. Error in percent of meter reading for vertical angles turned for FlowTracker, Price AA and pygmy meters

	Error (in percent)		
Angle Turned (deg.)	FT P1515	AA A99053	Pygmy P97080
80	1.1	232.8	289.0
70	-3.5	97.4	114.4
60	1.7	40.6	57.2
50	1.8	16.8	29.7
40	2.2	4.0	15.2
30	1.4	5.0	5.6
20	3.3	3.6	6.9
10	0.1	0.1	4.4
0	-0.5	-1.0	0.0
-10	0.0	-3.0	-7.7
-20	0.4	-5.7	-10.7
-30	-0.1	-5.6	-11.1
-40	-1.6	1.1	1.6
-50	-1.2	17.1	17.9
-60	-6.1	44.0	42.9
-70	-10.8	97.4	91.1
-80	-29.0	258.6	236.9

Table 8. Meter repeatability at a flow of approximately 2 ft/s

Meter	2 σ (in percent)
Flow Probe S/N 45610	1.5
Flow Probe S/N 45611	3.1
Flow Probe S/N 45613	2.0
Swoffer 2" prop #1	1.5
Swoffer 2" prop #2	2.0
Swoffer 3" prop #2	1.6
Swoffer 3" prop #12	2.3
FlowTracker S/N P1515	1.9
Price Type AA S/N A99053	2.2
Price pygmy S/N P97080	2.3

ACKNOWLEDGEMENTS

The author would like to acknowledge the generosity of the Streamkeepers of Clallam County of Port Angeles, Washington, who loaned several Swoffer 3 inch propeller assemblies for testing. Thanks are also extended to James "Blu" Dubuisson and Bryan Frierson of Oologah Technologies, Inc., for their expert data collection and laboratory operations.

REFERENCES

Fulford, J. M., 2001. Accuracy and Consistency of Water-Current Meters. Journal of the American Water Resources Association, Vol. 37, No. 5, October 2001. pp. 1215-1224.

Fulford, J.M., K.G. Thibodeaux, and W.R. Kaehrle, 1993. Repeatability and Oblique Flow Response Characteristics of Current meters. In: Hydraulic Engineering '93. Proceedings of Conference, Hydraulic Division, July 25-30, 1993, American Society of Civil Engineers, New York, NY, pp. 1452-1457.

Fulford, J.M., K.G. Thibodeaux, and W.R. Kaehrle, 1994. Comparison of Current Meters Used for Stream Gaging. In: Fundamentals and Advancements in Hydraulic Measurements and Experimentation. Proceedings of Symposium, Hydraulic Division, August 1-5, 1994, American Society of Civil Engineers, New York, NY, pp. 376-385.

Global Water Instrumentation, 2007. Digital Water Velocity Meter Features and Specifications on the Web, accessed February 23, at http://www.globalw.com/products/flowprobe.html.

Hubbard, E.F., G.E. Schwarz, K.G. Thibodeaux, and L.M. Turcious, 2001. Price Current-Meter Standard Rating Development by the U.S. Geological Survey. In: Journal of Hydraulic Engineering, Vol. 127, No. 4, April 2001, American Society of Civil Engineers, New York, NY, pp. 250-257.

SonTek/YSI, 2007. FlowTracker Handheld ADV Overview on the Web, accessed February 23, 2007, at http://www.sontek.com/product/flowtracker/flowtracker-ov.htm.

Swoffer Instruments, Inc., 2002. Model 3000 Operating Instructions, Swoffer Instruments, Inc., Seattle, WA, 28p.

Swoffer Instruments, Inc., 2007. Swoffer Instruments, Inc. Model 3000 Current meter, Flow Calculator – Datalogger on the Web, Accessed February 23, 2007, at http://www.swoffer.com/pdf/3000bulet06.pdf.