Ground Water and Surface Water Under Stress: Competition, Interaction, Solutions

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Edited by

Dennis Wichelns
The Rivers Institute at Hanover College

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

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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

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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

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Preface

The papers included in these Proceedings were presented during the **USCID Water Management Conference**, held October 25-28, 2006, in Boise, Idaho. The theme of the Conference, sponsored by the U.S. Committee on Irrigation and Drainage, was ***Ground Water and Surface Water Under Stress: Competition, Interaction, Solutions***.

Competition for surface water and ground water continues to increase in the western United States and in many other regions. The demand for high-quality water in agriculture, industry and recreation, and for environmental and municipal uses, is increasing, while the supply remains largely fixed. Moreover, ground and surface water interact in complex ways that require that management of the two be considered in an integrated way. Persistent drought conditions in the American West have generated intense consideration of many technical and policy issues regarding surface water and ground water resources. Key issues include modeling the interaction of surface water and ground water, implementing conjunctive use programs, allocating and adjudicating water rights, and developing long-term strategies for optimizing the use of limited water resources.

The Conference provided a forum to discuss the many issues relating to surface and ground water supplies.

Papers included in the Proceedings were invited or accepted in response to a call for papers. The authors are professionals from academia; federal, state and local government agencies; water districts; and the private sector.

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

Dennis Wichelns
Hanover, Indiana

Conference Chairman

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OVERVIEW OF THE PECOS RIVER BASIN

Peter Burck[1]
Brian Wahlin[2]

ABSTRACT

The Pecos River originates east of Santa Fe, New Mexico and flows across the eastern portion of the state and southwestern portion of Texas before it empties into the Rio Grande. Most of New Mexico's fresh water is stored in aquifers below the ground. There are three major aquifers within the Pecos River Basin: the Fort Sumner groundwater basin, the Roswell groundwater basin, and the Carlsbad groundwater basin. All three of these basins have a shallow alluvial aquifer that is highly connected to the Pecos River. In addition, the Roswell and Carlsbad basins have deep artesian carbonate aquifers. Surface water in the Pecos River Basin comes from three main sources: snow melt in the Sangre de Cristo Mountains, flood inflow from storm events, and groundwater base inflow.

The management of water resources in the Pecos River Basin is strongly driven by agriculture. There are several small-scale acequias in the northern part of the basin and three large irrigation districts in the central and southern portion of the basin: the Fort Sumner Irrigation District (FSID), the Pecos Valley Artesian Conservancy District (PVACD), and the Carlsbad Irrigation District (CID). All of these entities rely heavily on surface water and/or groundwater supplies from the Pecos River Basin. Four major reservoirs have been constructed along the main stem of the Pecos River to provide flood control for the area and to supply irrigation water for CID.

In addition to the various agricultural demands, the Pecos River Basin is subject to demands from two other sources. First, there is an environmental demand to provide enough water in the Pecos River for the Pecos bluntnose shiner, which is listed as a threatened species under the Endangered Species Act (ESA). Second, New Mexico must deliver a certain amount of water to Texas according to the Pecos River Compact and Amended Decree.

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[1] Hydrologist, New Mexico Interstate Stream Commission, PO Box 25102, Santa Fe, NM 87504, 505-827-6162, peter.burck@state.nm.us
[2] Senior Hydraulic Engineer, WEST Consultants, Inc., 960 W. Elliot Road, Suite 201, Tempe AZ 85284, 480-345-2155, bwahlin@westconsultants.com

INTRODUCTION

The motivation for this paper is to provide background information about the Pecos River Basin in support of subsequent companion papers. The surface water supply in the Pecos River Basin, located in the eastern half of New Mexico, is renewed by rain, melting snow, and groundwater inflow. There are three major groundwater basins in the Pecos River Basin. A direct hydrologic link exists between the surface water sources and the groundwater sources in the Pecos River Basin. Groundwater can contribute to surface water, and surface water can contribute to groundwater. Also, depleting surface water can deplete groundwater supplies and vice versa. Because of annual variations in precipitation and snowfall, the surface water yield from the Pecos River Basin has historically been unreliable. In addition, there are many demands (e.g., agricultural, environmental) placed on the limited water supply in the Pecos River Basin.

BASIN INFORMATION

The Pecos River originates in the Sangre de Cristo Mountains in Mora County, New Mexico. It flows south across eastern New Mexico for approximately 300 miles through San Miguel, Guadalupe, De Baca, Chaves, and Eddy counties in New Mexico before it enters Texas (see Figure 1). In Texas, the river flows southeast for another 400 miles before it reaches Amistad Reservoir and its confluence with the Rio Grande. The total drainage area of the Pecos River in New Mexico and Texas is about 44,000 square miles. Most of its tributaries, which in New Mexico include the Gallinas River, the Rio Hondo, the Rio Felix, the Rio Penasco, the Black River, and the Delaware River, flow from the west. The topography of the river valley ranges from mountain pastures in the north, with an elevation of more than 13,000 feet above sea level, to grasslands, semiarid irrigated farmlands, desert with sparse vegetation, and, in the lowermost reaches of the river, deep canyons. The land surface elevation in the vicinity of the New Mexico-Texas border is about 2,800 feet above sea level.

Surface Water

The surface water in the Pecos River Basin is derived from three sources: snowmelt, flood inflow, and groundwater inflow, or base inflow (Longworth and Carron, 2003a). Runoff from snowmelt originates from snowfall in the Sangre de Cristo Mountains. Runoff from summer monsoonal storms also contributes significantly to the surface water supply of the Pecos River. These flood inflows can occur anywhere along the river and generally are the biggest source of surface water (Longworth and Carron, 2003a). Flood inflows are quite variable. Large storm events can quickly fill up the major reservoirs on the Pecos River. Extended periods of time may elapse with little to no flood inflow. There are three primary locations where groundwater inflow contributes significantly to the surface water supply: the Puerto de Luna area (Dinwiddie and Clebsch, 1973), the Roswell-Artesia area, and the Carlsbad area. The base inflow in the Roswell-Artesia area comes from the Roswell groundwater basin. Inflows from this aquifer vary significantly. Base inflow in the Carlsbad area comes from the Carlsbad groundwater basin as well as seepage from Lake Avalon and return flows from irrigation (Longworth and Carron, 2003a).

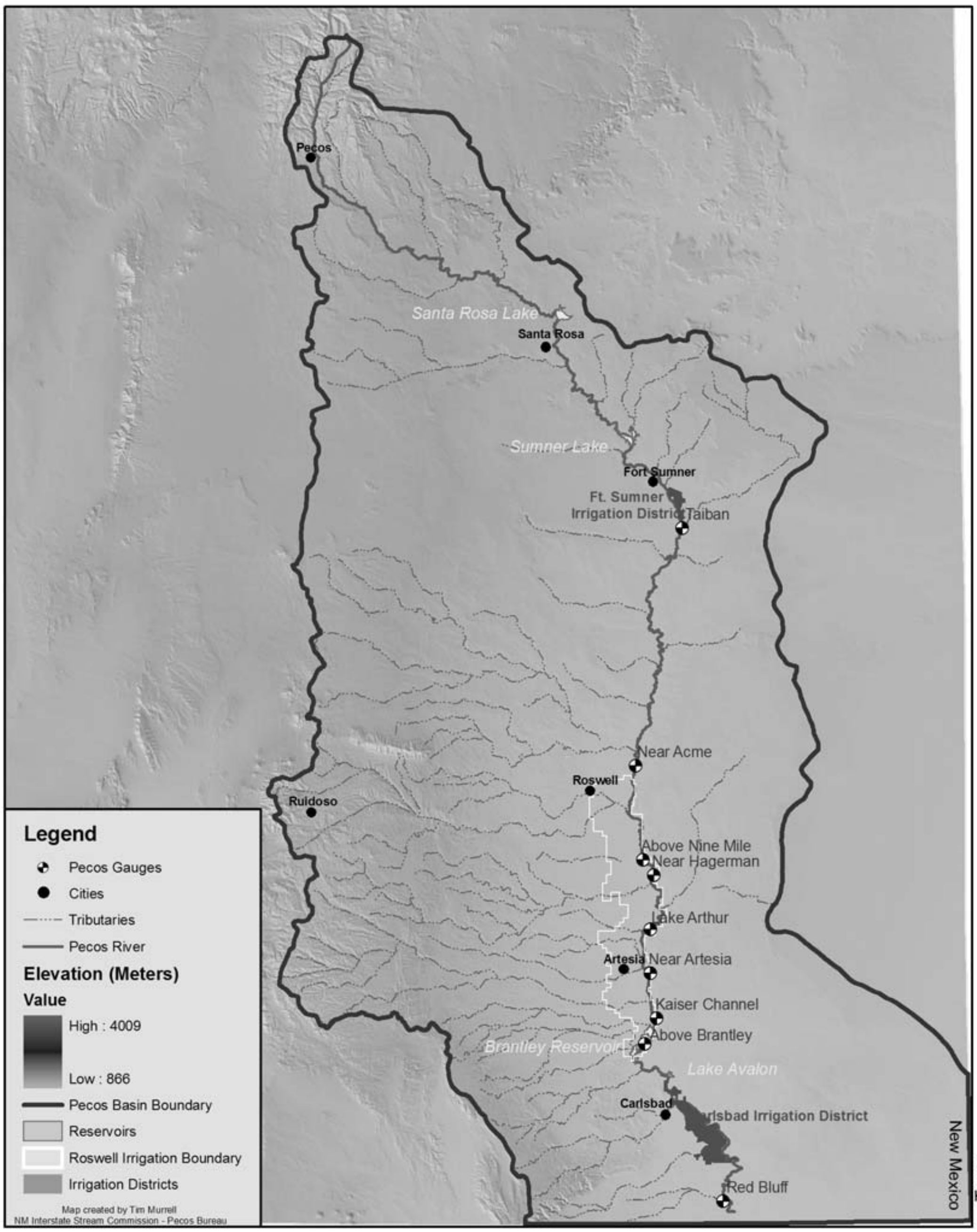

Figure 1. Map of Pecos River Basin

Groundwater

Three major water-bearing basins exist within the Pecos River Basin: Fort Sumner, Roswell Artesian, and Carlsbad. All three of these basins have a shallow alluvial aquifer that is highly connected to the Pecos River. The Roswell and Carlsbad basins also have deeper artesian aquifers.

The Fort Sumner basin is the smallest of the group. The shallow alluvial aquifer serves as the source of water for a number of irrigators in the area.

The Roswell Artesian groundwater basin is a productive artesian aquifer that is overlain by a thick confining unit and topped off by a shallow alluvial aquifer (Barroll and Shomaker, 2003). In the early part of the 20th century, the Roswell area was famous for its high-capacity artesian wells, which would deliver water to the surface without pumps and were thought to provide an endless source of water. The extensive use of the artesian wells has since de-pressurized the aquifer and, for the most part, water no longer flows to the surface freely (Barroll and Shomaker, 2003).

The cavernous limestone of the Capitan reef forms the Carlsbad groundwater basin, which delivers good quality water. The Capitan reef is a thick accumulation of limestone beds (Barroll and Shomaker, 2003).

MAJOR DAMS AND RESERVOIRS

Four major reservoirs store Pecos River water in New Mexico: Santa Rosa, Sumner, Brantley, and Avalon. All four reservoirs are used to store water for the Carlsbad Project, a US Bureau of Reclamation irrigation district. In general, the two upstream reservoirs (Santa Rosa and Sumner Reservoirs) are the preferred water storage locations because evaporation losses are typically lower than in the downstream reservoirs. The locations of these dams and reservoirs can be seen in Figure 1. Properties of the various reservoirs are shown in **Table 1**.

The Pecos River Compact limits the Carlsbad Project's total entitlement storage in all four reservoirs combined to 176,500 acre-feet. Total conservation storage is the sum of the entitlement storage, the minimum pool and the estimated sediment accumulation.

Santa Rosa Dam and Reservoir

Santa Rosa Dam (originally called Los Esteros Dam) impounds a drainage area of about 2,400 square miles. The dam was completed in 1980, and it is owned and operated by the US Army Corps of Engineers. The purpose of Santa Rosa Dam is to provide flood control, sediment retention, and storage of irrigation water for CID. Santa Rosa Dam and Reservoir offers 25 miles of shoreline with recreational activities available such as boating, fishing, swimming, camping, hiking, and bird watching.

Table 1. Pecos River Basin Reservoir Properties

Reservoir & Year Completed	Storage Capacity (acre-feet)	2006 Entitlement Storage (acre-feet)	Minimum Pool (acre-feet)	Estimated Sediment Accumulation (acre-feet)	Total Conservation Storage (acre-feet)
Santa Rosa (1980)	439,900	92,398	0	3,853	96,251
Sumner (1937)	94,750	40,236	2,500	190	42,926
Brantley (1988)	1,008,000	40,000	2,000	788	42,788
Avalon (1907)	4,466	3,866	600	0	4,466
Total		**176,500**			

Sumner Dam and Reservoir

Sumner Dam (formerly known as Alamogordo Dam) is an earthfill dam that was completed in 1937. The dam is owned by the US Bureau of Reclamation and operated by CID. The total drainage area above Sumner Dam is about 3,900 square miles, with about 2,400 square miles located above Santa Rosa Dam and 1,500 square miles of drainage area located between the two dams. The purpose of Sumner Dam is to provide flood control and to store irrigation water for CID. Santa Rosa and Sumner Dams are operated jointly to provide optimal flood control in the Pecos River Basin. Sumner Dam and Reservoir offers 60 miles of shoreline and a variety of recreational activities.

Brantley Dam and Reservoir

Brantley Dam is a concrete gravity dam that was completed in 1988. Brantley Dam is owned by the US Bureau of Reclamation and operated by CID. The drainage area above Brantley Dam is about 18,000 square miles, which includes the drainage area above Santa Rosa Dam and Sumner Dam. This dam was built to replace McMillan Dam, which was declared unsafe. The US Bureau of Reclamation drained and breached McMillan Dam in 1991. The purpose of Brantley Dam is to provide flood control, to store irrigation water for CID, to enhance fish and wildlife, and to provide recreation. Brantley Dam and Reservoir offers recreational activities such as boating, fishing, swimming, hunting, camping, hiking, and bird watching.

Avalon Dam and Reservoir

Avalon Dam was initially completed in 1891. This dam was destroyed twice by floods and reconstructed. Construction was completed on Avalon Dam in its present form in 1907. Avalon Dam is a small dam that is operated primarily as a diversion structure for CID and provides only incidental benefits in the event of minor floods. Avalon Dam is owned by the US Bureau of Reclamation and operated by CID. Avalon Dam and Reservoir offers limited recreational activities.

IRRIGATION DISTRICTS

The Pecos River Basin is home to three irrigation districts: the Fort Sumner Irrigation District (FSID), the Pecos Valley Artesian Conservancy District (PVACD), and the Carlsbad Irrigation District (CID). Several small acequias are situated in the northern part of the basin. The locations of the various irrigation districts can be seen in Figure 1.

Fort Sumner Irrigation District

Fort Sumner was established in 1862 when the U.S. Government detained Apache and Navajo Indians there. As an experiment, 6,000 acres of land were farmed in the area. In spite of efforts to farm the land, hardships suffered by the Indians were so great that the irrigation experiment was abandoned in 1868. The Fort Sumner Land and Canal Company was formed in 1906 and development of an irrigation system began soon after. The system was sold to FSID in 1918 (Shomaker, 2003).

FSID, which now covers about 6,500 acres of land, holds a superior diversion water right (1903) for not more than 100 cfs from the natural flow of the Pecos River. Water is released from Sumner Dam to FSID in amounts equal to the reservoir inflow, but not exceeding 100 cfs. No water can be stored behind Santa Rosa Dam or Sumner Dam for FSID. FSID's diversion delivery is set every two weeks using a procedure developed by the New Mexico Office of the State Engineer (NMOSE).

Pecos Valley Artesian Conservancy District

The Pecos Valley Artesian Conservancy District (PVACD) was formed in 1932 in order to conserve water from the Roswell Artesian groundwater basin located between Roswell and Artesia. Initially, it was thought that the Roswell Artesian groundwater basin provided a limitless supply of water. However, by 1925 it became apparent the pressure in the artesian aquifer was declining. Since its formation, PVACD has plugged more than 1,500 wells, installed water meters, and undertaken other water conservation measures (Shomaker, 2003). PVACD does not have rights to any of the surface water stored behind Santa Rosa Dam or Sumner Dam or flowing in the river itself. Instead, PVACD irrigators rely entirely on groundwater. Today, approximately 120,000 acres of land are irrigated within the district.

Carlsbad Irrigation District

The Spanish started irrigating the lower Pecos Valley around 1600. Irrigation in the early 19th century flourished under the Spanish land grant colonization system and was continued after 1850 by the American settlers. The early irrigation systems were community ditches, which diverted the normal flow of the river without the benefit of permanent diversion structures. In 1888, a large ranch was located near Carlsbad. The ranch manager initiated the first large-scale irrigation attempt. Since the natural characteristics of the area required a more comprehensive treatment than the enterprise could afford, it failed. For the next 17 years, various private interests attempted unsuccessfully to make this project financially profitable (USBR, 2006).

The US Bureau of Reclamation took over the project in 1906, made significant improvements to the system, and constructed Sumner Dam. In 1932, the Carlsbad Irrigation District (CID) was formed. The newly established CID had the authority to operate the US Bureau of Reclamation's dams, issue bonds for improvements to the system, and collect fees from landowners for use of the system. CID includes 25,055 acres of irrigable land. These lands extend for 20 miles along the Pecos River, three to five miles in width. The project's irrigation system serves more than 700 persons on 155 farms. CID has the senior storage water right (1888, 1915, and 1919) on the lower reach of the Pecos River in New Mexico. Water can be stored behind Santa Rosa Dam, Sumner Dam, Brantley Dam, and Avalon Dam for use by CID.

Acequias

Acequias, or community ditches, are recognized under New Mexico law as political subdivisions of the state. Many of New Mexico's acequia associations have been in existence since the Spanish colonization period of the 17^{th} and 18^{th} centuries. Historically, they have been a principal local government unit for the distribution and use of surface water. The associations have the power of eminent domain and are authorized to borrow money and enter into contracts for maintenance and improvements. Acequia associations do not have the power to tax, so the expenses of maintenance and improvements are the responsibility of the individuals served by the irrigation system (NMOSE, 2005).

ENDANGERED SPECIES

The Pecos River Basin contains a wide variety of wildlife. One of these animals, the Pecos bluntnose shiner (Figure 2), has been the center of much controversy. This small minnow has been classified as threatened by the US Fish and Wildlife Service (Service). Many of the operational procedures for the dams and reservoirs have been changed in an effort to improve the habitat for the Pecos bluntnose shiner. Specifically, efforts have been made to avoid drying of the Pecos River in the upper critical habitat north of Roswell and to avoid prolonged releases of irrigation water from Sumner Dam.

Figure 2. The Pecos bluntnose shiner

PECOS RIVER COMPACT AND AMENDED DECREE

In 1948, New Mexico and Texas entered into the Pecos River Compact, which dictated the amount of water that New Mexico was legally obligated to deliver to the Texas state line on the Pecos River. In 1988, as a result of a lawsuit filed by Texas, the US Supreme Court entered an Amended Decree, which appointed a federal River Master on the Pecos River and established an accounting system to verify water deliveries to the New Mexico-Texas state line (King and Sims, 2005). The terms of the Amended Decree allow New Mexico to deliver a surplus to Texas, but a net deficit delivery during a three-year accounting period is not permitted. The responsibility of meeting the state line delivery requirements fell to the New Mexico Interstate Stream Commission (NMISC), a companion agency to the NMOSE. New Mexico's failure to comply with the terms of the Compact and Amended Decree could result in federal intervention, whereby the state would lose its ability to manage its water on the Pecos River (King and Sims, 2005). Since this time, New Mexico has tried aggressively to meet the requirements of the Pecos River Compact and Amended Decree by examining and implementing a variety of short-term and long-term programs aimed at conserving water.

CONCLUSION

The Pecos River provides water for a variety of uses in southeastern New Mexico. Many demands are placed on the limited resource. Among these demands are interstate stream delivery obligations, irrigated agriculture, and threatened and endangered species.

REFERENCES

Barroll, P., and Longworth, J. (2003). "Regional hydrology of the Roswell Artesian Basin and the Capitan Aquifer." *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future*, Decision-Makers Field Conference, New Mexico Bureau of Geology and Mineral Resources, Socorro, NM, 23-27.

Dinwiddie, G.A. and Clebsch, Jr., A. (1973). *Water Resources of Guadalupe County, New Mexico*. Hydrologic Report 3, New Mexico State Bureau of Mines and Mineral Resources, Socorro, NM.

King, R., and Sims, E. (2005). "Solving water needs in the Pecos River Basin." *Southwest Hydrology*, 4(4), 26-31.

Longworth, J. and Carron, J. (2003a). "Surface water hydrology of the Pecos River." *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future*, Decision-Makers Field Conference, New Mexico Bureau of Geology and Mineral Resources, Socorro, NM, 20-22.

Longworth, J. and Carron, J. (2003b). "Overview of water operations in the Pecos River Basin." *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future*, Decision-Makers Field Conference, New Mexico Bureau of Geology and Mineral Resources, Socorro, NM, 32-38.

New Mexico Office of the State Engineer (NMOSE). (2005). "Office of the State Engineer: Interstate Stream Commission: Acequias." http://www.ose.state.nm.us/isc_acequias.html.

Shomaker, J.W. (2003). "How we got here: a brief history of water development in the Pecos basin." *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future*, Decision-Makers Field Conference, New Mexico Bureau of Geology and Mineral Resources, Socorro, NM, 61-64.

US Bureau of Reclamation (USBR). (2006). "Carlsbad Project." http://www.usbr.gov/dataweb/html/carlsbad.html.

INTEGRATING WATER MANAGEMENT IN EGYPT: FROM CONCEPT TO REALITY

Eng. Maher Khodary[1]
Eng. Nabil Fawzi[2]
Eric Viala[3]

ABSTRACT

Managing water resources is becoming an increasingly difficult task, from technical, economic, social, and political perspectives. This is especially true in Egypt where multiple and growing demands are competing for a limited water supply.

In order to deal with increasingly complex technical issues, the Ministry of Water Resources and Irrigation (MWRI) has over the years set up various specialized units and departments able to deal with drainage, groundwater, water quality, and irrigation improvement issues. This has facilitated the implementation of specific projects and activities but the resulting fragmentation drastically hampers cross-sectoral coordination, timely decision-making, and thus modern (integrated) water management.

Acknowledging this situation, the MWRI has recently taken steps to simplify its structure, starting with its local delegations, districts which cover on average 50,000 feddans or acres. 27 Integrated Water management Districts (IWMDs) now exist in Egypt, covering about 15 % of the national irrigated area, with benefits in terms of water management acknowledged by both Ministry officials and water users.

INTRODUCTION

Egypt's water supply relies almost exclusively on the Nile River through the huge reservoir behind the High Aswan Dam: Lake Nasser. Out of an annual inflow of about 84 billion cubic meters, Egypt's share is set by international agreement with

[1] Lower Egypt Resident Advisor, USAID-funded LIFE-IWRM Project managed by International Resources Group - formerly Head of the Irrigation Sector, Ministry of Water Resources and Irrigation, Cairo, Egypt

[2] Upper Egypt Resident Advisor, USAID-funded LIFE-IWRM Project managed by International Resources Group - formerly Chairman of the Egyptian Public Authority for Drainage Projects, Ministry of Water Resources and Irrigation, Cairo, Egypt

[3] Senior IWRM Resident Advisor, USAID-funded LIFE-IWRM Project managed by International Resources Group, Cairo, Egypt - eviala@iwrmeg.org - eviala@irgltd.com

Sudan at 55.5 billion cubic meters. Alternative water sources are limited and involve erratic and meager precipitations (average annual rainfall being less than 2 inches over most of the country), fossil groundwater whose extraction is a "one-time shot", and expensive and yet underdeveloped desalination technologies.

The demand for fresh water resources has, on the other hand, steadily increased over the years, along with the population growth and industrialization, thus reducing the per capita share. Egypt recently became a water scarce country (i.e. with less than 1,000 m3/capita/year).

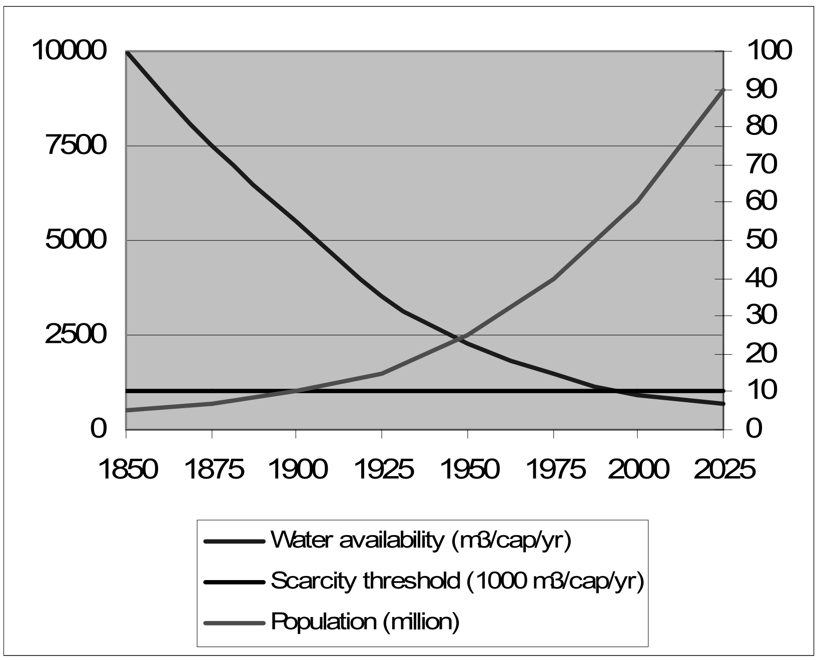

Figure 1. Evolution of the per capita water share in Egypt.

Traditionally, the MWRI's role has chiefly been to distribute water. But facing the challenge of increasing water demands with limited options to increase the supply, the MWRI has taken steps towards water management. Concepts such as water savings, and water use efficiency have now became planning priorities if not yet management objectives.

One of the essential components of the evolution towards (integrated) water management is to ensure the existence of a proper institutional framework where decision-making is delegated as much as possible ("subsidiarity" principle). In Egypt, this turns to be quite a challenge because of the highly fragmented organization of the MWRI.

CURRENT INSTITUTIONAL SETUP: A MINISTRY COMPARTMENTALIZED INTO SPECIALIZED ENTITIES

The MWRI (previously Ministry of Public Works and Water Resources, MPWWR) is significantly the oldest Ministry in Egypt, being about 150 years old. Traditionally, the MWRI's role has chiefly been to ensure that all users (irrigation, domestic and industrial needs, navigation) receive enough and timely water resources to address their needs[4]. But managing water resources has over the past 50 years become a more complex task: drainage and water quality issues have now significant impacts, while modern agriculture has much higher requirements regarding water supply.

As a consequence, the MWRI has over the years diversified the technical capacity of its staff in order to tackle new responsibilities, such as drainage construction and maintenance, water quality monitoring, groundwater development and management, coastal protection, operation & maintenance of pump stations, etc. Specific units, departments or entities have also been established. Donor agencies contributed significantly to this development with each new project requesting a specific project unit to ensure timely and efficient implementation[5].

Today the MWRI is divided into several departments, authorities, sectors and units (see figure 2 next page). The main ones are:

- Irrigation Department (ID), which manages irrigation and subdivides into several sectors, some of these being:
    - Irrigation Sector (IS), responsible for maintaining canals and allocating water;
    - Irrigation Improvement Sector (IIS), which implements irrigation improvement projects (IIP);
    - Ground Water Sector (GWS), responsible for managing and monitoring groundwater resources;
    - Planning Sector (PS), in charge of formulating and evaluating long and short term water management plans;

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[4] Other ministries are to some extent involved in managing water resources:

- The Ministry of Housing, Utilities and Urban Communities (MHUNC), is responsible, through municipal water authorities, for treating and delivering drinking water.
- The Egyptian Environmental Affairs Agency (EEAA) assesses and monitors water use impacts on the environment; and
- The Ministry of Health and Population analyses, and reports on water quality in relation to potential health hazards.

[5] Moreover existing field staff is rarely involved during project implementation but ultimately responsible for operating and maintaining the new development or improved structure.

- Egyptian Public Authority for Drainage Projects (EPADP), originally responsible for implementing drainage projects, but which over the years has taken over the entire maintenance of drains;
- Mechanical & Electrical Department (MED), in charge of the maintenance and operation of all pump stations (irrigation, drainage, drainage reuse);
- National Water Research Center (NWRC), with its twelve specialized research institutes, which conducts applied research on irrigation and water management; and
- The High Aswan Dam Authority (HADA), which operates and maintains the Aswan dam and reservoir.

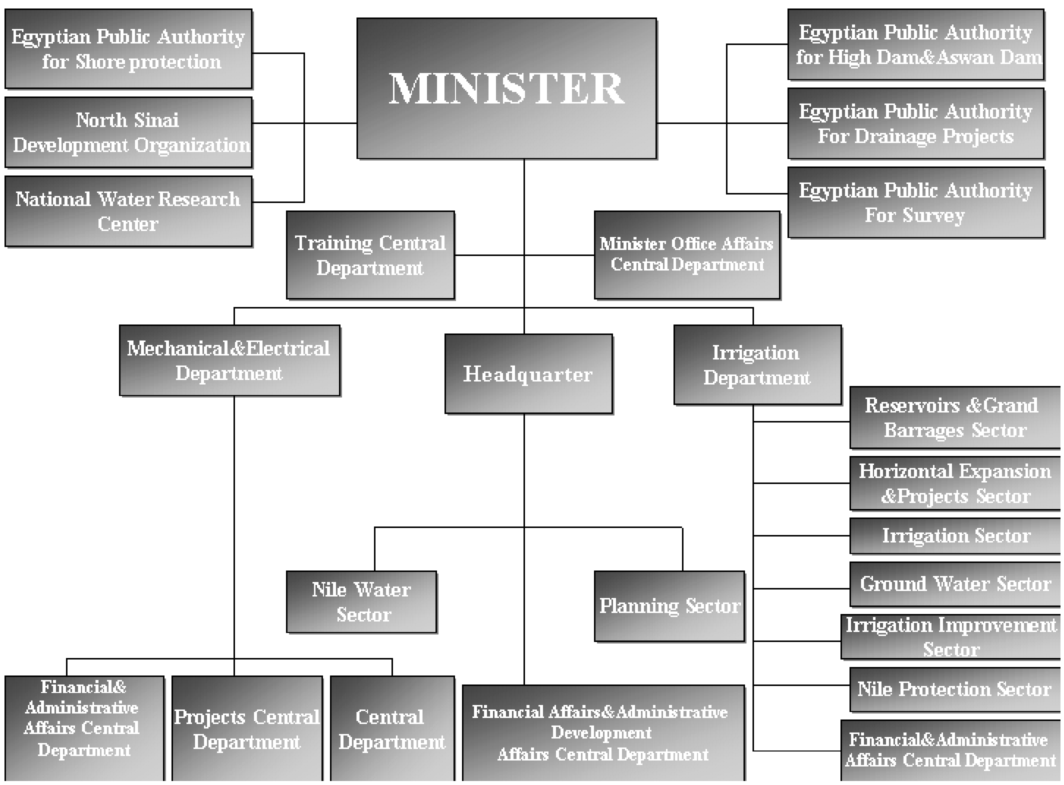

Figure 2. Main MWRI entities.

In addition to these large entities, there are a number of small units with more limited responsibilities and functions, such as the Central Directorate for Irrigation Advisory Service (CD-IAS), the Integrated Water Management Unit (IWMU), the Institutional Reform Unit (IRU), the Water Quality Unit (WQU), the Water Communication Unit (WCU), etc.

At central level, each main agency (EPADP, MED, ID, NWRC) reports only to the Minister and thus operates quite independently. The yearly planning of activities of each entity is carried out based on sound technical criteria but social, environmental and cost-efficiency criteria are marginally considered. There is also limited, if any, consideration for the planning of other entities, and consequently limited cross-sectoral or geographic integration.

At regional level, the country is divided into central directorates, each headed by an undersecretary. This MWRI undersecretary has nominal supervision over all MWRI activities. The various MWRI central departments, sectors and authorities function however separately with their own local delegations such as general directorates, inspectorates and districts (see figure 3 below). The boundaries of these do not generally match (at directorate level or below) from one sector/department/agency to another.

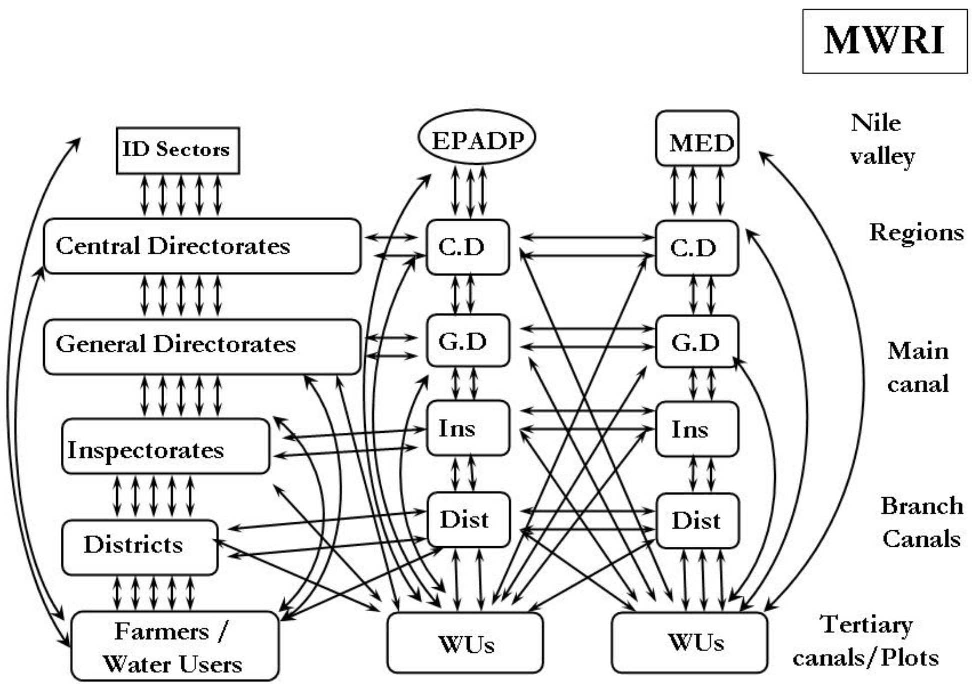

Figure 3. Breakup of the regional and local MWRI entities.

The most significant example of this fragmentation is the Egyptian Public Authority for Drainage Projects. Originally established in 1973 as the implementing unit for the first of the World Bank-funded series of National Drainage Projects, the EPAPD has steadily grown over the years and extended its responsibilities. In the late 1980s, the EPADP thus became responsible for not only building (open and sub-surface) drains but also for maintaining existing drains all over Egypt. To fulfill this mission, the EPADP has thus established its own parallel administration, with regional Directorates divided into local districts. The EPADP has grown so much over the years that it moved into its own separate building. Today, although field staff from both Irrigation Department and EPADP strive to coordinate at their level, it is as if these are two separate Ministries, with separate budgets, plans and policies.

The breakup of the MWRI into separate, specialized sectors/departments/agencies allows better execution of technical activities, notably in terms of project implementation. Conversely this fragmentation prevents integration and coordination. There is limited holistic understanding of what the overall water management situation is in any command area. As a result, parallel operation & maintenance, management and/or improvement activities may contradict or counter-impact each other.

Conversely, the situation is also quite complex for water users: they not only lack a mechanism to identify and express their needs, priorities or concerns, but also have to navigate in a bureaucratic maze to find the proper MWRI official to talk to (e.g. registering a well cannot be done with the local irrigation district but at the regional office of the groundwater sector, so few bother to register).

A PROCESS OF DECENTRALIZED INTEGRATION

Although Integrated Water Resources Management (IWRM) has been a common buzzword in water communities around the world for some time now, it is often a challenge for many water managers to propose a practical translation of the concept. The same applies to Egypt, where IWRM is an official MWRI policy and is frequently quoted by MWRI managers. But while the concept has been accepted, few are able to outline a concrete process to implement IWRM. The main issue is how to define integration as it relates to management.

Multi-disciplinary integration (inclusion of social, environmental and economic perspectives in engineering designs and processes) has been progressively adopted as a technical evolution of working standards and practices. But geographic or cross-sectoral integration is an institutional change, and thus easily perceived as a threat to their established authority by directors and managers. AREV Earlier institutional reform efforts in developing countries focused on central administrative levels, striving to improve coordination and information flows, clarifying roles and responsibilities, providing standards and guidelines for technical and human resource management. Most of these efforts logically fell short for the same reasons: they required a change in mentalities, and through lack of follow-up (a project rarely lasts more than five or six years), lack of long term commitment and political will, achievements were marginal or unsustainable. Impacts were also limited in terms of improved management of water resources, and actual benefits for water users.

Today most institutional change efforts focus on the local level, in order to:

- Promote decentralization and delegation;
- Empower water users, and get them involved in the management process;

- Bring direct benefits to beneficiaries; and thus
- Demonstrate tangible and replicable achievements.

The idea is to democratize the entire management process, by empowering both water users and local managers. It is hoped that the combination of demonstrated benefits and bottom up pressure for more accountability and transparency will eventually make its way up and affect all administrative layers.

In Egypt, USAID and the MWRI agreed in 2002 to establish four Integrated Water Management Districts (IWMDs) as a pilot activity. The idea was to consolidate all water management functions at district level (about 20,000 hectares) into one sole MWRI entity. Simultaneously, Branch Canal Water User Associations (BCWUAs) were to be established to involve stakeholders in the management of water resources.

The IWMD concept was defined as follows: "IWMD is an entity that has sufficient manpower, material, and fiscal resources to operate and maintain all water resources under its jurisdiction. Implementing integrated water management at the district requires integration of staff, facilities, stakeholders, information, users, and water resources" (see also figure 4 next page). The IWMD represents a unique venue to coordinate all water management activities and implement water projects, thus resulting in more appropriate decisions, more sustainable implementation and significant economies of scale.

Progress was initially slow, as the idea faced several challenges:

- Delineating the boundaries of the new IWMDs, since the existing districts (mostly irrigation and drainage) covered somewhat different areas; this was addressed by mostly focusing on irrigation districts as the most hydrologic units;
- Defining the roles and responsibilities of the new IWMDs, while roles and responsibilities of other entities had to be accordingly updated;
- Transferring staff, equipment, facilities, vehicles to the new IWMDs; the usual amount of "red tape" obstacles and delays had to be dealt with; and
- Developing water user participation: this required to demonstrate and raise awareness about benefits for both water users and MWRI staff; thankfully previous efforts funded by USAID and other donors had already paved the way in that direction.

This initial effort proved however successful, convincing MWRI managers of the viability of the concept of decentralized integration, and demonstrating immediate benefits to both MWRI staff and water users (see next section). In October 2004, USAID answered to the MWRIs' request and started funding a similar but scaled-up effort, the LIFE-IWRM Project, as a component of the larger LIFE program (LIFE stands for Livelihood Incomes From the Environment).

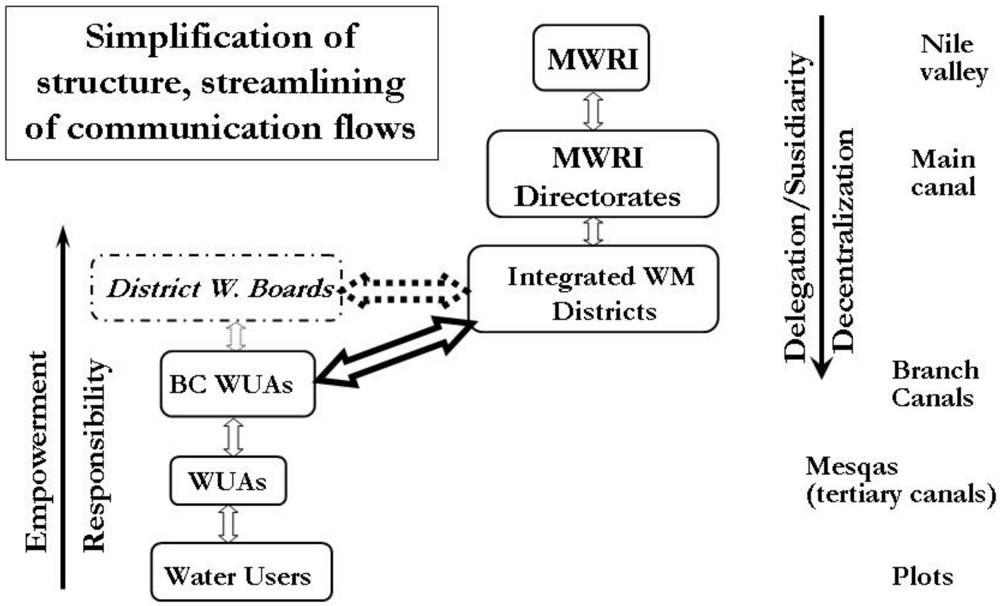

Figure 4: The reorganized setup at district level.

The LIFE-IWRM Project has been targeting 5 entire directorates in Egypt (total of over 1 million feddans/acres, 15 % of Egypt's irrigated area). Three main tasks have been carried out:

- Establishment of IWMDs: 23 new IWMDs (adding to the four pilot ones for a total of 27) have been set up through the integration of most water management functions (irrigation and drainage O&M, quantitative and qualitative water monitoring, etc.), with project support for the definition of boundaries, identification of facilities, assignment of managers and staff, transfer of equipment, updating of roles and responsibilities;
- Formation of Branch Canal Water User Associations (BCWUAs) in all IWMDs: on average 25 BCWUAs (each covering 1500 to 2000 feddans/acres) are being formed in each IWMD; project support has focused on the definition of the process (steps and corresponding guidelines), preparation and implementation of training events for data collection and planning, WU awareness raising, election of representatives, activation of BCWUAs, communication between BCWUAs and IWMDs, monitoring and evaluation; and
- Equitable allocation of water resources: IWMD staff have been identified, assigned, and trained to carry out specific water monitoring activities; project has been providing computers and water monitoring equipment, training IWMD staff to use this equipment, and supporting the implementation of related data-based water management activities.

The three tasks are complementary in the sense that the overall objective is to empower local managers and water users to:

- Monitor the amount, availability, quality, and use of their water resources;
- Identify and prioritize water management issues; and
- Solve local problems and conflicts in a decentralized, collaborative manner.

DECENTRALIZED INTEGRATION: RESULTS AND BENEFITS

Several significant institutional benefits from the establishment of IWMDs have been identified and acknowledged by MWRI staff:

- Pooling of resources, equipment and skills at local level (mainly through the consolidation of irrigation & drainage functions): IWMD managers point out that they are able to carry out more activities, better serve water users, and use equipment more intensively;
- Streamlined communication channels: MWRI General Directors (covering four or five districts), are pleased with the empowerment and responsiveness of IWMD managers and staff; and
- Decentralized and simplified decision-making (notably for water distribution with the removal of the inspectorate administrative layer).

In parallel, the formation of BCWUAs has also demonstrated significant results:

- IWMD staff mention improved communications with water users, fewer violations and complaints, improved conflict resolution, and better identification and prioritization of maintenance needs;
- Water users, on the other hand, welcome the enhanced communication with IWMD staff, improved internal conflict resolution, and better tackling of their needs and priorities; most importantly, water users and stakeholders value the “single window contact” that the IWMD became.

At central level, MWRI senior officials have come to recognize that more activities can be implemented by IWMD staff (with technical support from central level), thus resulting in significant savings in time, costs and logistical resources[6].

Promoters of IWRM have now come to acknowledge that IWRM requires not only institutional and technical changes but also an evolution of the socio-cultural environment. The formation of IWMDs has resulted in a significant change in mentality and behavior:

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[6] Interesting enough, MWRI “old timers” compare the current IWMDs to the irrigation districts that existed until the 70s. Water management at the time was handled by one irrigation engineer.

- The performance of IWMD staff has improved substantially, both in terms of commitment and technical capacity; and
- MWRI senior officials are progressively acknowledging that IWMD staff are to be seen as the “frontline soldiers” of the MWRI: they are the ones dealing on a daily basis with water resources and water users, solving technical issues as well as allocation conflicts and disputes.

This mentality change is clearly demonstrated by the revised approach for establishing BCWUAs. Until recently, the formation of BCWUAs used to be carried out and managed by the CD-IAS (Central Directorate for Irrigation Advisory Service) while IWMD staff were remotely involved as data providers and to handle logistics. With approval from the MWRI, the LIFE-IWRM Project has promoted a decentralized approach whereby IWMD staff directly facilitate the formation and activation of BCWUAs. This new approach:

- Promotes a direct partnership between BCWUAs and the IWMD;
- Ensures sustainability (even after project’s end) by building the capacity of IWMD staff;
- Reinforces the IWMD as sole MWRI entity at local (district) level; and
- Reduces the cost of establishing/strengthening BCWUAs over all of Egypt by empowering existing field staff.

NEXT STEPS

While the formation of IWMDs all over Egypt requires an additional effort from the MWRI, further steps are also being considered, such as:

- The establishment of district water boards to federate all BCWUAs at district-level; and
- The integration of MWRI directorates.

REFERENCES

International Resources Group (IRG), Red Sea Sustainable Development and Improved Water Resource Management, Improved Water Management Component, Final Report, September 2004

Ministry of Water Resources and Irrigation, National Water Resource Plan, June 2005

Ministry of Water Resources and Irrigation, Feasibility Study for the Integrated Irrigation Improvement and Management Project (IIIMP), Final Report, January 2005

PECOS RIVER DECISION SUPPORT SYSTEM: TOOLS FOR MANAGING CONJUNCTIVE USE OF SURFACE AND GROUND WATER RESOURCES

John Carron[1]
Jim McCord[2]
Ali Elhassan[3]
Peggy Barroll[4]
Tomas Stockton[5]
Miguel Rocha[6]

ABSTRACT

The New Mexico Office of the State Engineer (OSE), Interstate Stream Commission (ISC), and the U.S. Bureau of Reclamation, have developed a suite of models, the Pecos River Decision Support System ("PRDSS"), which simulates major components of the groundwater and surface water hydrology and water operations associated with the Pecos River from Santa Rosa Reservoir to the New Mexico-Texas Stateline. The significant interdependencies between the Pecos River and the underlying aquifer systems and the significant response of the river to changes in ground water use makes it imperative to evaluate management activities with a basin-wide perspective. The need for these models arose from several distinct activities: the New Mexico State Engineer's administration of groundwater resources, negotiations involving the adjudication of the Pecos River, two ongoing Environmental Impact Statements (EIS), and New Mexico's need to determine how the Pecos River system can be managed to ensure water delivery obligations to Texas under the Pecos River Compact and Amended Decree are met. Under these programs, land and water retirement, water leasing, augmentation well management, supplemental water supplies and replacement water supplies are all actively used components of water management in the Pecos River Basin.

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[1] Hydrosphere Resource Consultants, Inc., 1002 Walnut St., Suite 200, Boulder, CO 80302; jcc@hydrosphere.com.

[2] Hydrosphere Resource Consultants, Inc., 115A Abeyta Street, Socorro, New Mexico 87801; jtm@hydrosphere.com.

[3] New Mexico Interstate Stream Commission, P.O. Box 25102, Santa Fe, New Mexico 87504-5102; ali.elhassan@state.nm.us.

[4] New Mexico Office of the State Engineer, P.O. Box 25102, Santa Fe, New Mexico 87504-5102; peggy.barroll@state.nm.us.

[5] Stockton Engineering, 1827 Aliso Drive NE, Albuquerque, NM 87110; tbstockton@comcast.net.

[6] U.S. Bureau of Reclamation, 555 Broadway Ave. NW, Albuquerque, NM 87107; mrocha@uc.usbr.gov.

INTRODUCTION

This paper describes the need for and development of a suite of modeling tools (the Pecos River Decision Support System or PRDSS) to simulate the effects of water management actions in the Pecos River Basin, New Mexico. The models were developed and refined largely independently of one another over a 15 year span. Beginning in 2000, and as a result of two significant basin-wide policy-affecting activities, these modeling tools were brought together and linked to form a single tool for evaluating the combined effects of surface and ground water management actions across the basin. One of these actions is the Pecos River Adjudication Settlement Agreement, which settles outstanding water rights claims and provides a permanent mechanism to meet New Mexico's obligations under the Pecos River compact and to avoid the need for a priority call on the river. The second is the Carlsbad Project Water Operations and Water Supply Conservation EIS, whose primary purposes are to conserve and protect the threatened Pecos Bluntnose Shiner and to conserve the Carlsbad Project water supply.

The models were extensively tested and peer reviewed in a public forum, as part of the Carlsbad Project Water Operations and Water Supply Conservation EIS. As part of the tests, the models were calibrated to reproduce the hydrologic history of the Pecos River system. Once calibrated, the models were used to evaluate effects of current and/or proposed management activities on a variety of resource indicators throughout the basin. This paper provides an overview of the Pecos River and the PRDSS modeling tools, and two companion papers by New Mexico Interstate Stream Commission staff further illustrate the model applications and the institutional setting for water management in the Pecos River Basin.

HYDROLOGY AND WATER OPERATIONS

The Pecos River originates in the Sangre de Cristo Mountains of north central New Mexico, and travels from there through southeastern New Mexico in to Texas (figure 1). It merges with the Rio Grande near Del Rio Texas, about 150 miles east of Big Bend National Park. Snowmelt from the Sangre de Cristo Mountains is a significant source of the river's reliable water supply. From these mountains, the river travels through desert or semi-desert regions where ephemeral tributary inflows are generated by very unpredictable and highly variable precipitation events. In addition to inflows from precipitation events, the river receives significant base inflow from underlying aquifers in southeastern New Mexico. The models described in this paper are used to simulate water operations and hydrologic conditions in the highlighted area of figure 1.

The primary use of both surface and ground water in the study area is agricultural irrigation. Two irrigation districts (Carlsbad and Fort Sumner), irrigate up to 25,000 and 7,000 acres, respectively. The primary water supply source for these districts is the Pecos River. About 60% of the irrigated acreage in the Carlsbad Irrigation District (CID) has supplemental well rights, which allow those acres to be irrigated by ground water from the underlying Carlsbad aquifer system when surface water supplies are limited. The Carlsbad Project – a Reclamation Project – operates four main-stem reservoirs on the Pecos River with a combined conservation storage capacity of 176,500 acre-feet. CID historically is the sole user of Carlsbad Project water, and historically diverts about 75,000 acre-feet annually for its irrigators.

Figure 1. The Pecos River Basin with highlighted study area.

The Pecos Valley Artesian Conservancy District (PVACD) irrigates approximately 120,000 acres almost exclusively with groundwater pumped from aquifers in the Roswell Artesian Basin, which lies under and west of the Pecos River in the central part of the study area. The Roswell aquifers provide a significant source of water to the Pecos River as base inflows. These base inflows in turn are a significant source of water for the CID. Ground water extraction by PVACD irrigators over the last 60 years has caused a significant reduction in base inflows to the Pecos River.

Operation of the four Carlsbad Project reservoirs is guided primarily by the need to store and deliver water to CID, and to bypass sufficient water to meet FSID's right, which has the senior *direct flow* right in the study area. The historic operation of these reservoirs with respect to CID's water is based on the need to maximize storage and delivery efficiency. Generally, the water is stored preferentially in the upstream reservoirs (Santa Rosa and Fort Sumner). Water from these upstream reservoirs is delivered downstream to Brantley and Avalon only when it is need. This provides multiple benefits; the first is a potential reduction in evaporation losses, the second is increased capacity for capturing flood inflows in Brantley reservoir downstream, and the third is a reduction in transport losses. Transport losses are minimized by delivering water in "blocks". These "block releases" are staged releases of water (over 1000 cfs) released at a constant rate for 14 to 20 days. These block releases occur two to three times per year, depending on supply and demand within the CID (Longworth and Carron, 2003b).

INSTITUTIONAL NEEDS DRIVING MODEL REQUIREMENTS

Development of the Pecos River Decision Support System was driven by multiple parallel needs including NEPA activities surrounding the federally threatened Pecos Bluntnose Shiner, settlement of outstanding water rights adjudication claims, and ongoing efforts by New Mexico to meet its obligations under the Pecos River Compact and Amended Decree. Management actions proposed or required as part of these activities include:

- Leasing or purchasing and transfer of water rights
- Operational modifications for purposes of meeting aquatic habitat requirements
- Water exchanges
- Augmentation of water supplies via ground water pumping
- Delivery of leased and/or purchased water to meet Pecos River Compact obligations
- Offsetting of increased depletions caused by altered operations

Most of these activities involve the conjunctive use of surface and ground water resources. The significant interdependencies between the Pecos River and the underlying aquifer systems and the significant response of the river to changes in ground water use makes it imperative to evaluate management activities with a basin-wide perspective.

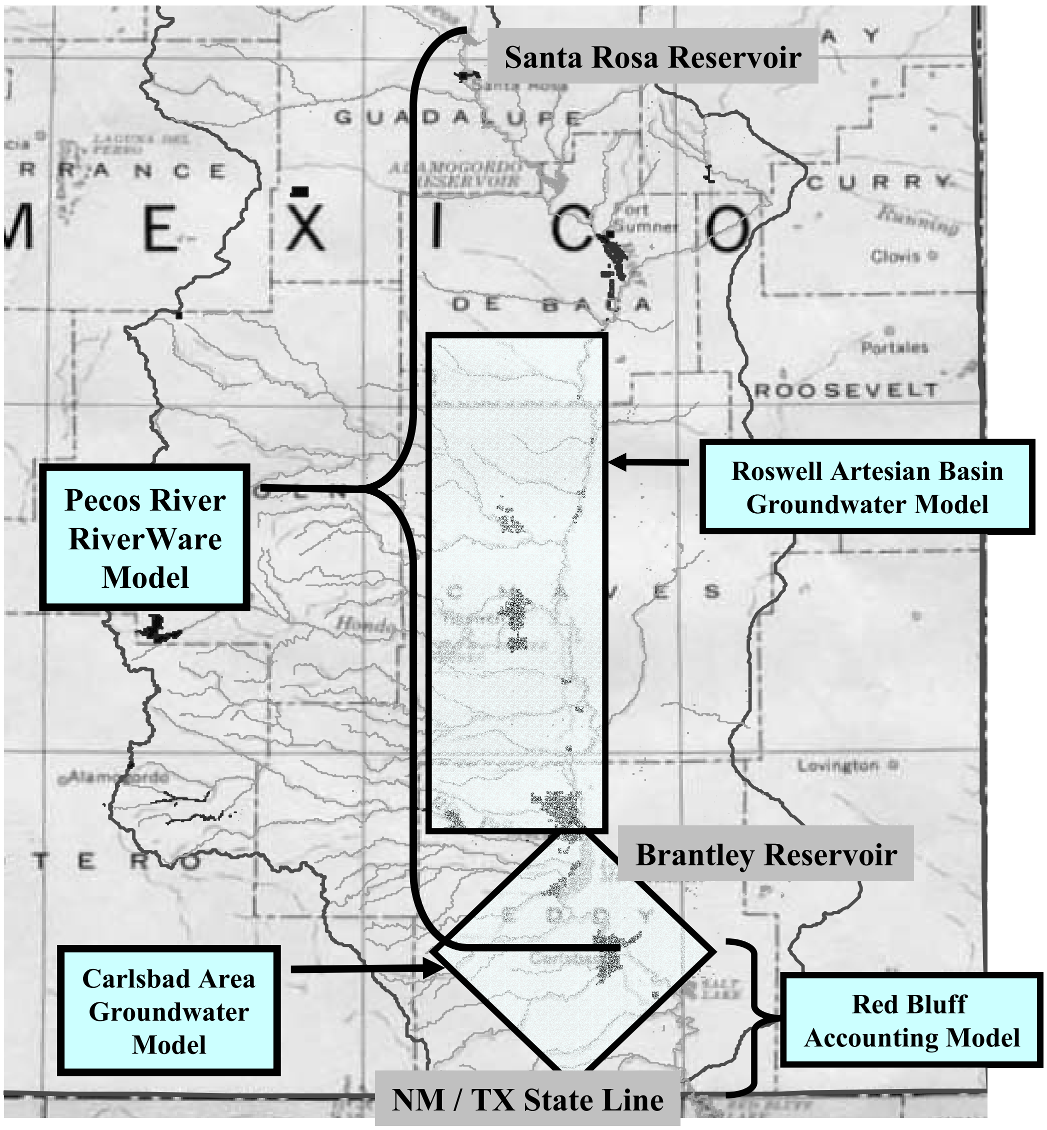

Figure 2. Spatial domain of the model elements of the Pecos River Decision Support System.

The PRDSS model suite (Figure 2) consists of

- A RiverWare surface water model of the Pecos River
- The Carlsbad Area Groundwater Model (CAGW) (A MODFLOW Model)
- The Roswell Artesian Basin Groundwater Model (RABGW) (A MODFLOW Model)

- The Data Processing Tool (DPT)
- The Red Bluff Accounting Model (RBAM), and
- Data management utilities and databases.

Each of these model components is discussed below.

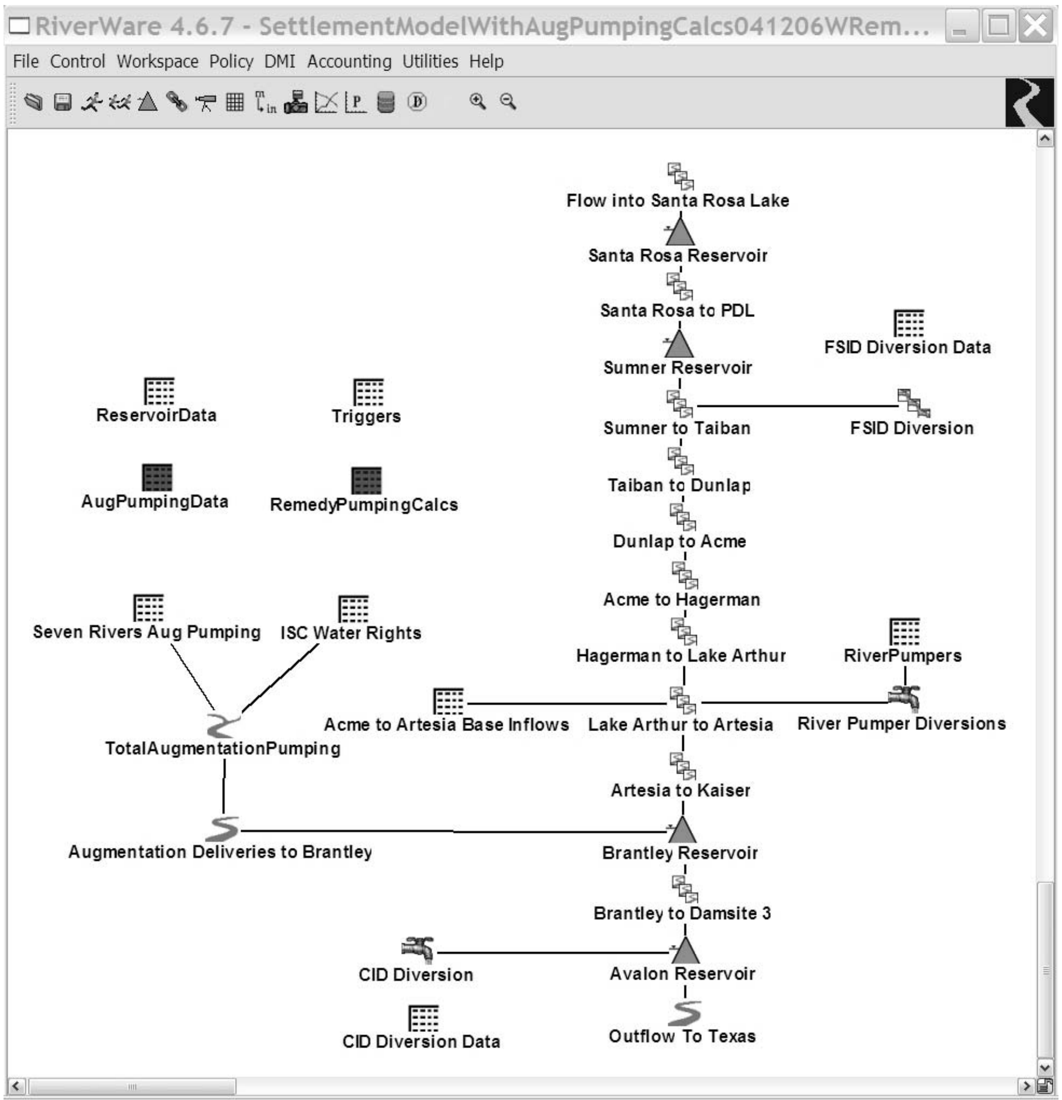

Figure 3. The Pecos River RiverWare model network.

PECOS RIVER RIVERWARE MODEL

River and reservoir operations from Santa Rosa Dam downstream to Avalon Dam are simulated by the Pecos River RiverWare model (Figure 3). The model uses historical river inflows for mainstem inflows to Santa Rosa reservoir and for gaged tributary inflows. Ungaged tributary inflows were derived from mainstem gage data. Base inflows from the Roswell Artesian Basin were developed from the RABGW model, and are influenced by changes in ground water usage for irrigation and other needs such as augmentation supply and exchange water. The model simulates the significant physical processes acting on the surface water system, including reservoir operations (spills, evaporative losses, bank storage, etc), river hydrology (routing, bank storage, evapo-transpiration, seepage), and diversions for irrigation (consumptive use, return flows, etc.). The model operates on a daily timestep using a rule-based simulation routine. The RiverWare rule-base simulation solver allows operational policy to be represented in the model environment by a series of prioritized “if-then” type statements. These simulation rules plus the hydrologic inputs drive the simulation, and provide a user-friendly approach to quickly and efficiently evaluate a variety of management options. RiverWare™ can simulate a wide range of rule types, allowing the ISC to consider flood operations, conservation storage, irrigation district operations, Pecos River Compact under-delivery contingencies, and endangered species needs.

THE ROSWELL GROUNDWATER MODEL

An important input to the RiverWare model is the inflow of ground water from the Roswell Artesian Basin to the Pecos River (represented graphically by the “Acme to Artesia Base Inflow” object in figure 3. These inflows are influenced by pumping in the basin, which intercepts ground water that would otherwise have discharged to the river. Inflows from the Roswell Artesian Basin may contribute as much as 50% of the annual surface water supply for the Carlsbad Project. Since these inflows could be modified by changes in the management of the ground water resource in the Roswell Basin, a physical process-based model was required. The Roswell Artesian Basin Groundwater Model (RABGW) was originally developed by OSE and ISC staff and consultants, using standard USGS MODFLOW software. The model is based upon decades of geologic and hydrologic investigation of the Roswell Basin, a huge set of water level and stream gage data, and has been developed, tested and refined by a number of different groups over the past 15 years. RABGW simulates the Roswell artesian aquifer, the overlying confining unit and shallow alluvial aquifer, and the interaction of these aquifers with the Pecos River (Barroll et al., 2003).

The RABGW model has been instrumental in understanding the effects of well pumping on base inflows to the Pecos River. One of the key findings from the RABGW model was a better understanding of the spatial and temporal variability in the effects of ground water extraction on base inflows, and the long period of response (as long as 100 years in some instances) that have significant bearing on management decisions.

THE CARLSBAD GROUNDWATER MODEL

Downstream from the Roswell Basin, the Carlsbad area contains two large aquifer systems, the Carlsbad Reef aquifer, and a shallow alluvial aquifer. Overlying these aquifers and significantly impacting their hydrology is the Carlsbad Irrigation District (CID). The Pecos River RiverWare model ends at Lake Avalon, which is the diversion structure for the Carlsbad Irrigation District (CID). RiverWare simulates the delivery of surface water through the river and reservoir system and ultimately into the CID Main Canal. Absent any flood control operations, all of the waters of the Pecos River are diverted into this canal, and the river typically has zero flow immediately below Avalon Dam (except for seepage from the Dam and the Main Canal itself). Return flows and seepage associated with irrigation in the District and natural base inflows from the aquifers therefore make up a very large component of New Mexico's delivery to Texas, which is recorded at the Red Bluff gage approximately 30 river miles below Avalon Dam. Irrigation is almost exclusively by flood irrigation. Surface water irrigation return flows and supplemental well pumping significantly impact the return flow and base inflow regimes in this region.

The Carlsbad Area Groundwater Model (CAGW) was developed by OSE and ISC staff and consultants, again using standard USGS MODFLOW software. The model is based upon substantial geologic and hydrologic investigations published by the OSE and USGS, and upon a large set of water level and stream gage data extending from the 1940's to the present day. This model simulates the shallow alluvial aquifer and the reef aquifer in the Carlsbad area, as well as natural and man-made sources of water to, and discharge of water from, those aquifers. The model calculates the outflow of ground water into the Pecos River, and also calculates water levels in both aquifers. The operations of the CID surface water irrigation system and its affect on aquifer flows are simulated based on inputs from the RiverWare model and computed additional supplemental well pumping that is used in times of surface water shortages (Barroll et al., 2003).

COMPACT ACCOUNTING AND OTHER DATA PROCESSING UTILITIES

An accounting model that tracks compliance with the Pecos River Compact, plus numerous data processing utilities are managed by a set of Access database and VBA tools. These utilities provide a user-friendly data management environment for performing data Input/Output between the various models and for scenario archiving and simulation results analyses. The tools constitute the "links" between RiverWare and the two MODFLOW models. They are used to generate stress files for ground water pumping and recharge for different scenarios, and perform temporal and spatial aggregation and dis-aggregation functions when moving data between models. One of the databases also serves as an archival tool and is a central repository for results and analyses generated as part of the NEPA programs ongoing in the basin.

SUMMARY

A suite of modeling tools (the Pecos River Decision Support System or PRDSS) has been developed to evaluate the impacts of both surface and ground water management options and their hydrologic interdependencies. The tools comprising the PRDSS have been peer reviewed in a public forum (the Carlsbad Water Operations and Water Supply Conservation EIS), and are currently being used to evaluate management options in two NEPA activities and a water rights adjudication proceeding. Companion articles in this conference proceeding describe application of the PRDSS (Elhassan and Carron, 2006; Sims and Smith, 2006)

REFERENCES

Barroll, Peggy, Eric Keyes, John Longworth, and Bhasker Rao. 2003. Modeling Hydrologic and Water Operations in the Pecos River Basin". *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future. Peggy S. Johnson, Lewis A. Land, L. Greer Price, and Frank Titus, Eds.* New Mexico Bureau of Geology and Mineral Resources. pp. 39-46.

Liu, Beiling, John Carron, and Jim McCord. 2003. "Evaluating the Consensus / Adjudication Settlement Plan: Application of the Pecos River Decision Support System". *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future. Peggy S. Johnson, Lewis A. Land, L. Greer Price, and Frank Titus, Eds.* New Mexico Bureau of Geology and Mineral Resources. pp. 112-115.

Elhassan, Ali, and John Carron. 2006. "Application of the PRDSS to the Pecos River Adjudication Settlement". *Ground Water and Surface Water Under Stress: Competition, Interaction, Solutions.* Proceedings of the USCID Water Management Conference, October 25-28, 2006.

Longworth, John, and John Carron. 2003a. "Surface Water Hydrology of the Pecos River". *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future. Peggy S. Johnson, Lewis A. Land, L. Greer Price, and Frank Titus, Eds.* New Mexico Bureau of Geology and Mineral Resources. pp. 20-23.

Longworth, John, and John Carron. 2003b. "Overview of Water Operations in the Pecos River Basin". *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future. Peggy S. Johnson, Lewis A. Land, L. Greer Price, and Frank Titus, Eds.* New Mexico Bureau of Geology and Mineral Resources. pp. 32-35.

Sims, Elisa N., and Coleman T. Smith. 2006. "Collaborative Solutions to Complex Problems: A Pecos River Basin, New Mexico Case Study". *Ground Water and Surface Water Under Stress: Competition, Interaction, Solutions.* Proceedings of the USCID Water Management Conference, October 25-28, 2006.

EVALUATION OF THE PECOS RIVER CARLSBAD SETTLEMENT AGREEMENT USING THE PECOS RIVER DECISION SUPPORT SYSTEM

Ali Elhassan[1] John Carron[2]
Jim McCord[3] Peggy Barroll[4]

ABSTRACT

The Pecos River Decision Support System (PRDSS) is a complex set of hydrologic models that simulates the hydrology and operations of key surface water and groundwater systems associated with the Pecos River. The PRDSS has been used in the development and evaluation of a complex water rights settlement agreement that is intended to help New Mexico achieve long-term compliance with the Pecos River Compact. The agreement anticipates that the State of New Mexico will purchase water rights, retire irrigated farmland, and operate wells to augment the flows of the Pecos River. The water rights acquired will be used to make deliveries to the state line as required by the Compact and to ensure certain water supplies to the Carlsbad Irrigation District. The PRDSS has been used extensively for evaluating the key terms of the Settlement Agreement using input data based on the historical hydrology records from 1967 to 1996 including river gages, pumping records and meteorological data. Two model scenarios were developed for this evaluation: the baseline scenario and the Settlement scenario that simulates the operation of the system under the Settlement Agreement. Several key resource indicators were identified to evaluate the results of the simulations. These include Pecos River compact obligations and departures, CID surface water allotment and supplemental well pumping and augmentation pumping in the Roswell basin.

The model results indicate that implementation of the Settlement agreement will:

1. Reduce the possibility of New Mexico defaulting on its Pecos River Compact obligations, and most likely result in credit over the long-term;
2. Increase the total annual surface water supply available to CID irrigators; and minimize the chances of a priority call by CID.

The PRDSS has proven a valuable tool for evaluating various actual or proposed management policies in the Pecos River basin.

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[1] Water Resources Engineer, New Mexico Interstate Stream Commission, P.O. Box 25102, Santa Fe, New Mexico 87504-5102; e-mail: ali.elhassan@state.nm.us
[2] Engineering Manager, Hydrosphere Resource Consultants, Inc., 1002 Walnut St., Suite 200, Boulder, Colorado 80302
[3] Senior Engineering Manager, Hydrosphere Resource Consultants, Inc., 1002 Walnut St., Suite 200, Boulder, Colorado 80302
[4] Senior Hydrologist, New Mexico Office of State Engineer, P.O. Box 25102, Santa Fe, New Mexico 87504-5102

INTRODUCTION

The Pecos River, which is a tributary of the Rio Grande, originates at an altitude of 12,000 feet in the Sangre de Cristo Mountains of north-central New Mexico.. The river flows southward through the semi-arid high plains of southeastern New Mexico and west Texas to join the Rio Grande near the town of Langtry, Texas.. A companion paper (Carron et al., 2006) describes the physical character of the river basin and provides and overview of water operations in the New Mexico sections of the river. The waters of the Pecos River are allotted between New Mexico and Texas by the terms of the Pecos River Compact of 1947 and an amended decree issued by the U.S. Supreme Court in 1988 after Texas sued New Mexico alleging violations of the terms of the original Compact.

The Supreme Court found that New Mexico had been under-delivering an average of 10,000 acre-feet of water each year for the past several decades. Since the 1988 ruling, New Mexico has met its Compact obligation shortfalls primarily through a series of short-term water leasing agreements. In March 2003, the State of New Mexico entered into an agreement with the Carlsbad Irrigation District (CID), the U.S. Bureau of Reclamation and the Pecos Valley Artesian Conservancy District (PVACD) regarding the adjudication of the Carlsbad Project Water Rights. This “Settlement Agreement” not only resolves certain outstanding water rights adjudication claims in the basin, but also provides a permanent mechanism for the State of New Mexico to meet its Compact obligations. Key components of the Settlement Agreement include purchase and retirement of irrigated lands and use of appurtenant ground water and surface water rights to meet Compact delivery requirements and to supplement the water supply of the Carlsbad Irrigation District.

This paper provides an overview of the Settlement Agreement, focusing in particular on the operational (hydrologic) components of the agreement. We then discuss the modeling of the Settlement Agreement components by the Pecos River Decision Support System (see companion paper by Carron et al.). The PRDSS was used to evaluate the terms of the Settlement, and to investigate how the Settlement might impact river operations and water supplies for other water users in the basin.

Pecos River Basin Overview

The Pecos river basin drains an area within New Mexico of approximately 20,000 square miles (**Figure 1**). In general, the climate of the basin is semiarid to arid with moderate winters and hot summers. The average annual precipitation over the greater portion of the basin varies between 11 and 16 inches annually. Seventy five to eighty percent of annual precipitation occurs during the period from May to October. Winter precipitation annual average is one-half inch in most parts of the basin except in the mountainous regions where it increases with elevation to over one inch.

Pecos River water has three primary sources. The first is snowmelt and runoff from the headwaters in the Sangre de Cristo Mountains, which averages about 55,000 acre-feet annually. The second source is overland flood flow, which is generated by precipitation, and on average provides between 20,000 – 300,000 acre-feet annually. The third source of Pecos River water is groundwater base inflow at three primary locations: springs located in and around Santa Rosa (36,000 – 60,000 acre-feet annually), Roswell to Artesia area (historically as high as 120,000 acre-feet annually, now approximately 15,000 to 20,000 acre-feet annually) and the Carlsbad area (20,000 – 30,000 acre-feet annually), **Figure 1**. The first two sources (snowmelt runoff and precipitation-based tributary inflows) are highly variable. The third source is less variable, although it is subject to significant impacts from ground water pumping.

There are primarily three processes that contribute to the reduction of flows in the Pecos River: natural evapotranspiration, seepage of water into the underlying ground water system, and human-induced consumptive use, mainly from irrigation. On average, approximately 110,000–120,000 acre-feet of Pecos River surface water is diverted for irrigation of crops. Two large irrigation districts, the Carlsbad Irrigation District (CID) and the Fort Sumner Irrigation District (FSID), use approximately 85 percent of the surface irrigation water. The remaining usage is by many individual irrigators who pump water directly from the river, and by small acequias, which are community operated irrigation canals. There are four primary reservoirs on the Pecos River that regulate the flow of the river (**Figure 1**). These reservoirs are used primarily to store irrigation water for CID and for flood control. They also provide recreational and environmental benefits.

Two major groundwater basins are directly connected to the Pecos River: the Roswell groundwater basin and the Carlsbad groundwater basin. The Roswell groundwater Basin consists of an extremely productive artesian (confined) aquifer that is overlain by a thick confining unit, and topped off by a shallow alluvial aquifer. In the early part of the 20th century, the artesian aquifer supported high-capacity artesian wells, from which water flowed freely at the surface without the need for pumps. Large groundwater diversions from the two aquifers support irrigation of more than100,000 acres. As mentioned earlier, the base flow from the Roswell basin is a major component of the Pecos River flow. Base inflow from the Roswell Basin has changed dramatically since the early 1900's, due in large part to the growth of ground water use for irrigation. In the Carlsbad basin there are two important aquifers: an alluvial aquifer associated with the Pecos River and its tributaries, and a karstic carbonate aquifer associated with the Permian Capitan Reef. When the surface water supply is inadequate, many CID members pump supplemental groundwater from these aquifers.

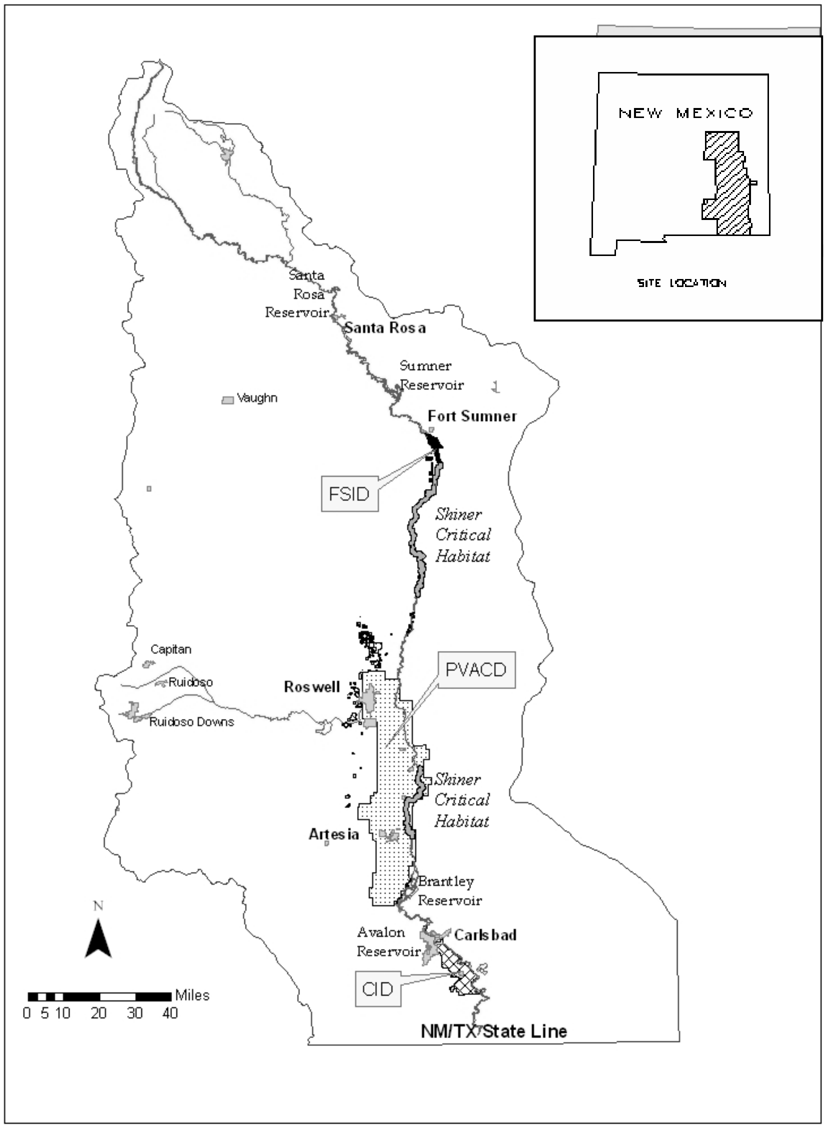

Figure 1. Map of the Pecos River Basin.

Pecos River Compact and Supreme Court Amended Decree

In 1948 New Mexico and Texas entered into the historic Pecos River Compact, and the negotiators were fully confident that the agreement would put conflicts between the states behind them (Thorson, 2003). The Pecos River Compact was intended to provide a means for dividing the surface waters of the river. However, only thirty years later, the states were before the U.S. Supreme Court to enforce and ascertain the meaning of the 1948 compact (op. cit). In 1974, Texas filed a suit in the U.S. Supreme Court complaining that New Mexico had failed to deliver all the water required by the compact. The Supreme Court eventually ruled that New Mexico had failed to meet compact obligations and required New Mexico to pay for past under-deliveries and thereafter to meet the delivery obligation every year (**Figure 2**). The court also issued in 1988 an amended decree appointing a River Master who determines New Mexico's annual obligation and compliance. New Mexico's obligation is determined by a complex set of instructions called the River Master's Manual. The primary factor in determining New Mexico's obligation is flood inflow. Flood inflow is determined by an examination of USGS stream flow gage records combined with a series of hydrologic calculations. It includes releases from Sumner Dam and the total overland and tributary flows accumulating to the Pecos between Sumner Dam and the state line. The manual provides that roughly 50 percent of the flood inflow to the basin must be delivered to Texas over a three-year period. Therefore, each year, New Mexico is required to deliver one-sixth of the current and one-sixth of each of the previous two-year's flood inflows.

Since 1988, New Mexico has achieved compliance largely through short-term leasing of irrigation water rights (**Figure 2**). Due to a potential compact delivery shortfall in 2001, discussions on a long-term solution to the compact compliance problem began between water users and stakeholders in the Pecos basin. These discussions resulted in the "consensus plan" and ultimately led to an adjudication settlement agreement on the Carlsbad project water rights, which is known as the Pecos River Carlsbad Settlement Agreement.

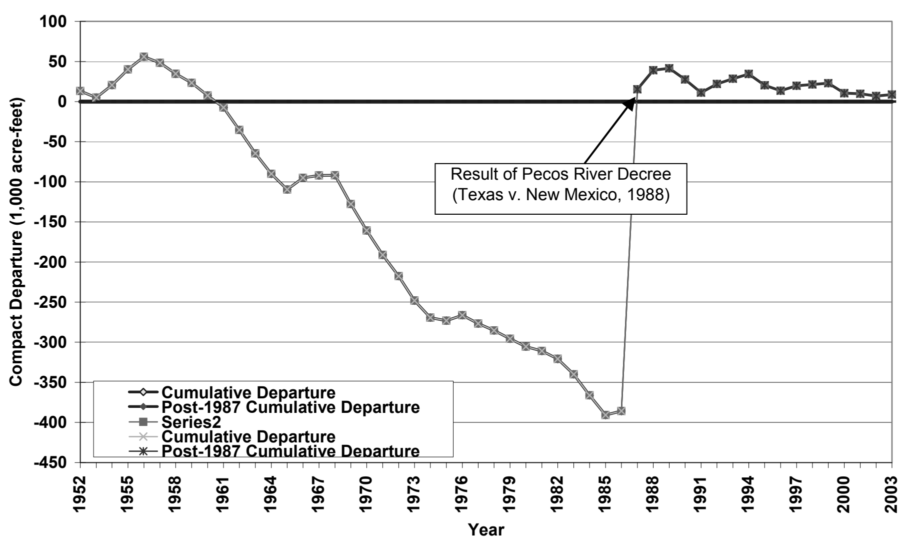

Figure 2. Pecos River Compact Cumulative Departure
1952-2003

THE PECOS CONSENSUS/ SETTLEMENT PLAN

In January 2003, the State of New Mexico entered into an agreement with the Carlsbad Irrigation District, the U.S. Bureau of Reclamation and the Pecos Valley Artesian Conservancy District regarding the adjudication of the Carlsbad Project Water Rights. The settlement adjudicates the water rights of CID, provides for an annual water allotment of 3.697 acre-feet per acre to CID members, and establishes a schedule for delivery of water to the state line. Implementation of the settlement requires satisfaction of the conditions precedent, which include: entry by the court of a partial final decree; adjudication of CID's water rights; implementation of the consensus plan which anticipates that the State of New Mexico will purchase water rights, retire irrigated farmland, and operate wells to augment the flows of the Pecos River; and completion of federal National Environmental Policy Act (NEPA) requirements.

The water rights acquired will be used to make deliveries to the state line as required by the Compact to avoid future under deliveries and to accumulate a net compact credit. These water rights will be used also to ensure certain water supplies to the Carlsbad Irrigation District to avoid future priority calls. The key components of the consensus plan include:

- Purchase and retirement of appurtenant water rights for 6,000 acres of land within CID;
- Purchase and retirement of 11,000 acres of land within PVACD;
- Delivery of the state owned CID water from Lake Avalon directly to the state line, subject to certain limits;
- Pumping from wells in the Roswell artesian basin to supplement Pecos River flows and to augment CID's surface water supply in low-supply years, up to the supply target levels shown in **Table 1**, subject to annual pumping limits of 35,000 acre-feet and a 5-year accounting period limit of 100,000 acre-feet.

Table 1. CID Surface Water Supply Thresholds for Augmentation Pumping (Effective Brantley Reservoir Storage)

Target Date	Target Supply
March 1	50,000 acre-feet
May 1	60,000 acre-feet
June 1	65,000 acre-feet
July 15	75,000 acre-feet
September 1	90,000 acre-feet

MODEL ANALYSIS AND RESULTS

Modeling Tools and Processes

The Pecos River Decision Support System (PRDSS) suite of models was used to evaluate the impacts of the terms of the Settlement Agreement. The models include a RiverWare model of river and reservoir operations between Santa Rosa Reservoir and Avalon Dam, two MODFLOW groundwater models of the Roswell and Carlsbad groundwater basins (the RABGW and CAGW models, respectively), a Pecos River Compact accounting model, and various pre- and post-processing tools for performing data input/output functions and post-run analyses. These tools are described in greater detail in a companion paper by Carron et al. (2006).

Model Input Data and Assumptions

The models used input data based on the historical hydrology records, from 1967 to 1996 including river gages, pumping records and meteorological data, with current or proposed operational rules superimposed on the hydrologic record. This period contains years of higher water supply as well as years of lower water supply. Thus it allows an evaluation of the effectiveness of the Settlement Plan under a variety of hydrologic conditions. This period was selected, in part, because some of the components of the hydrologic system, such as groundwater pumping, are better defined and stream gaging data are generally more complete. The models are reliable for estimating the long-term impact of implementing the proposed action, but they have not being used to predict water supply conditions at specific times and locations.

Two model scenarios were developed for this evaluation. The Baseline scenario, as the name suggests, represents a pre-settlement baseline condition against which proposed actions may be evaluated. The second scenario - termed the Settlement scenario herein - simulates the operation of the system under the Pecos River Adjudication Settlement Agreement (the Settlement). The Settlement scenario is essentially a translation of the Settlement agreement into model rules and data. In addition to the settlement terms described in the previous section, other key modeling assumptions used in evaluation of the scenarios include:

• Combined surface water allocation plus supplemental well pumping in CID limited to 3.0 feet per acre per annum for the baseline, and 3.697 feet per acre per annum under the settlement scenario;

• CID surface water allotments based on decreed 25,055 acres, deliveries to 20,000 irrigated acres (baseline), or 19,055 irrigated acres + 6,000 equivalent acres of state water rights (settlement);

• PVACD alluvial ground water pumping rates based on recent (1991–2000) historical use patterns, extrapolated back to 1967, artesian aquifer pumping rates use historical data 1967–1996;

• Permanent land retirements by ISC and other agencies are represented in both scenarios; and
• Temporary lease programs for Endangered Species Act (ESA) compliance and Pecos River Compact compliance are not included in either scenario.

Simulation of the two scenarios, and evaluation of their results, provides an estimate of the changes in water supply that is expected when the Settlement agreement is implemented.

Results

For evaluation of the settlement scenario, several key resource indicators were identified to evaluate the results of the simulations. These include:
• Estimated Pecos River Compact deliveries and credits;
• CID surface water allotment and supplemental pumping rates; and
• Augmentation pumping of purchased PVACD water rights.

Results of the scenario evaluation indicate that the settlement terms would likely increase state-line flows by approximately 9,500 acre-feet annually. **Figure 3** shows the estimated Pecos River Compact cumulative departure for both scenarios. Note that although the baseline results show a net deficit, this is not necessarily an indication or prediction of future non-compliance. Rather, we want to focus on the net gain in deliveries, as indicated by the difference in compact deliveries between the two scenarios.

Under the Settlement, CID, which is relatively a senior downstream water right holder, will not attempt a priority call on Pecos River basin water rights if they have at least 50,000 acre-feet of divertable supply each year.

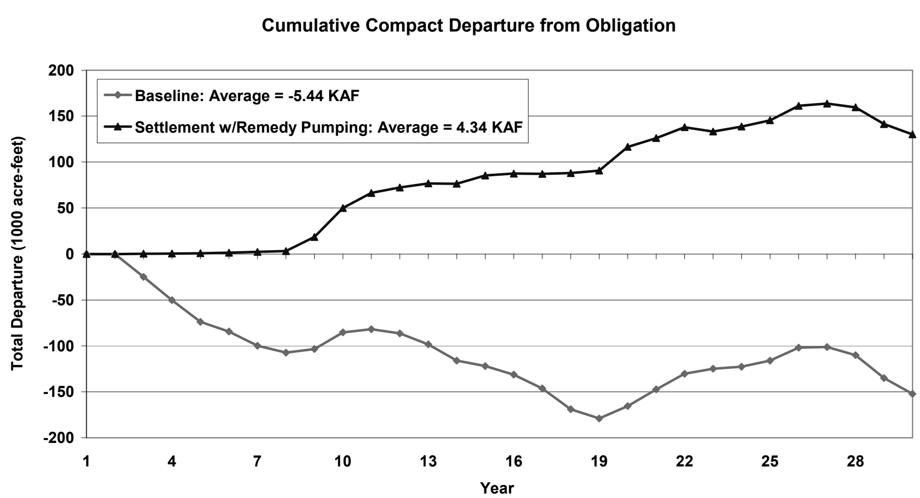

Figure 3. Comparison of Cumulative Compact Departure under the Baseline and Settlement Scenarios. (Carron, 2004)

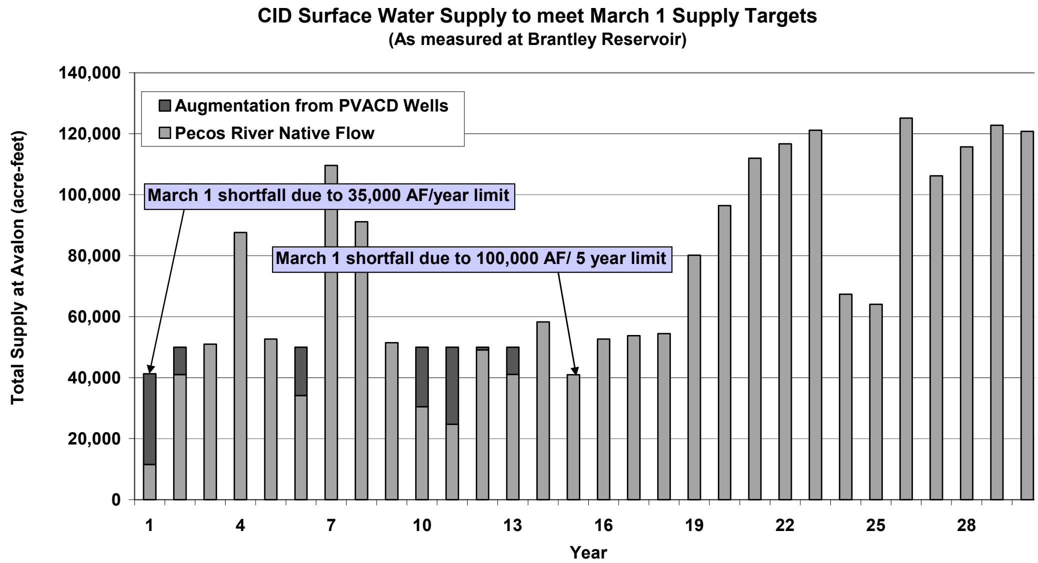

Figure 4. Augmentation Pumping required to meet 50,000 AF March 1 Supply Target (Carron, 2004).

To achieve this goal, ISC would use its purchased PVACD water rights to augment CID's surface water supply at times when the natural CID surface water supply is less than the prescribed thresholds (refer to Table 1). This means in practice that a need for a priority call is circumvented if CID's water supply reaches 50,000 acre-feet by March 1 (the beginning of the irrigation season) of each year. **Figure 4** illustrates the amount of augmentation pumping required to provide CID with 50,000 acre-feet of water on March 1 for each year under the settlement scenario and emphasizes the potential importance of augmentation pumping to the Pecos River in avoiding a priority call.

The total annual water supply available to CID under the settlement, including augmentation pumping, is shown in **Figure 5**.

The model estimated that ISC would pump an average of 12,500 acre-feet annually from its purchased PVACD water rights to augment the Pecos River flow as shown in **Figure 6**. A significant amount of augmentation pumping would occur in the first 10-15 years. During this time, the NMISC would be releasing most of its CID allotment to help build a credit at the state line. As a result, there would be less carryover water each year and a higher likelihood of additional augmentation pumping required to meet the CID target storage values. Over time, there would be fewer state line releases, more carryover, less augmentation pumping, and more aquifer recovery, which would further reduce the need for compact deliveries and augmentation pumping

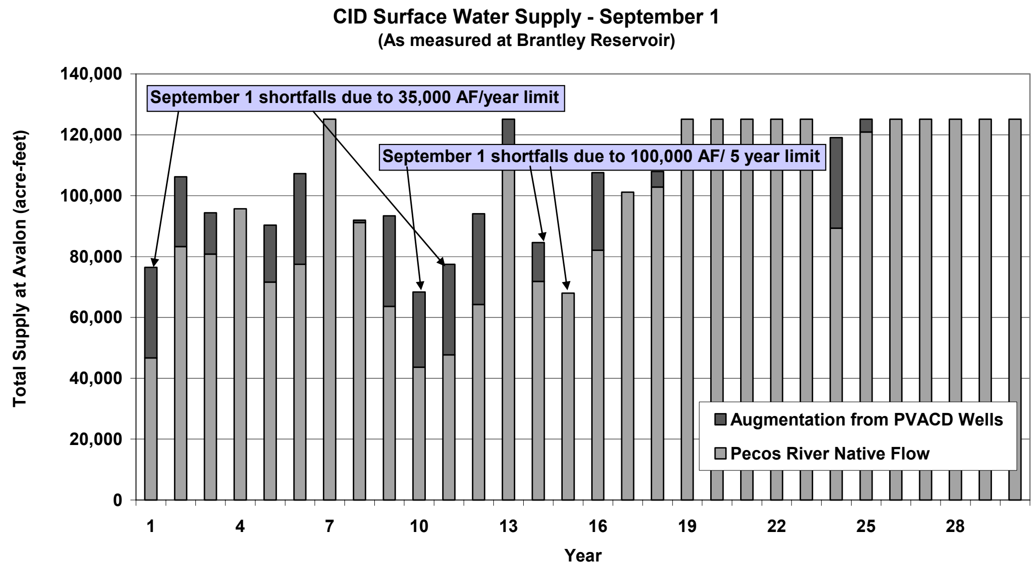

Figure 5. Total CID Supply from "Natural" and Augmentation Sources (Carron, 2004).

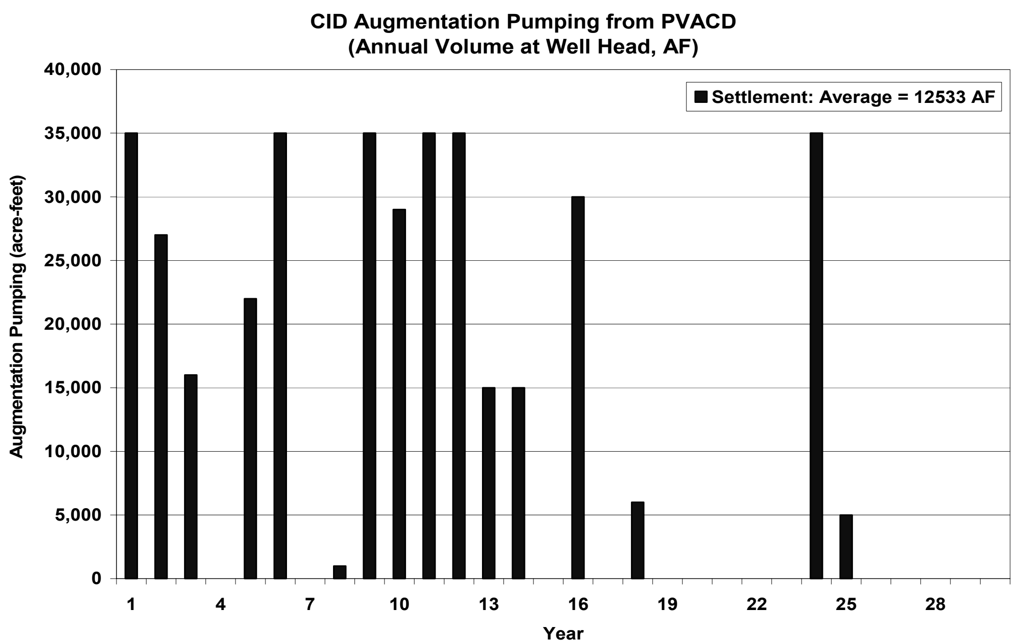

Figure 6. Settlement Scenario Augmentation Pumping from PVACD (Carron, 2004).

The average increase in water available for CID irrigators due to implementation of the Settlement is 0.22 feet per year **(Figure 7)**. Notice also that the Settlement tends to significantly benefit CID in dry years.Under the baseline scenario, the minimum final allotment was 1.5 feet per year, while under the Settlement; the minimum was about 2.2 feet per year. This benefit extends into the early part of the irrigation season as well. The minimum March 1 allotment increased from 0.55 to 1.21 under the Settlement scenario. This increase in early-season allotment translates into a higher proportion of early-season irrigation water coming from surface supplies as opposed to supplemental wells.

The increase in water available to CID irrigators due to implementation of the Settlement will benefit PVACD farmers by minimizing the chances of a priority call by CID from three times under the baseline scenario to zero time under the settlement scenario as can be seen in **Figure 5**.

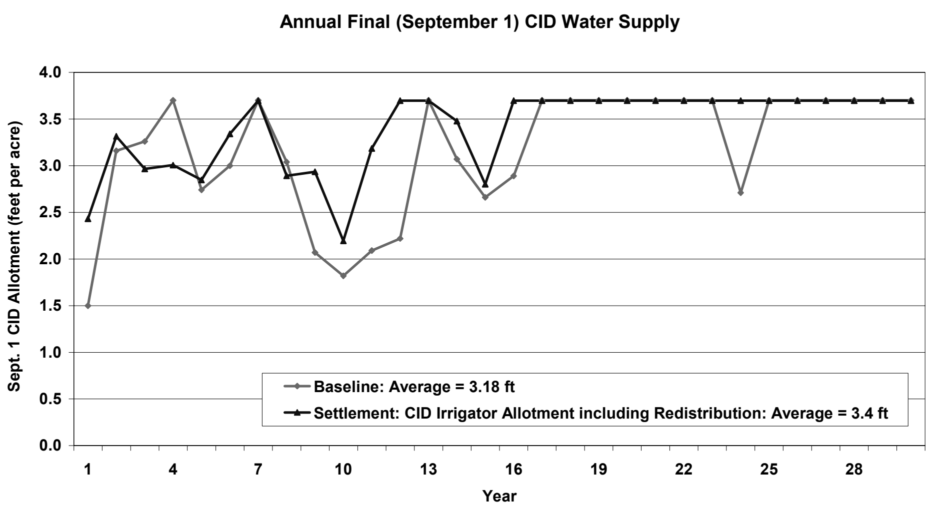

Figure 7. Comparison of CID Allotments under Baseline and Settlement Scenarios (Carron, 2004).

CONCLUSIONS

The model results indicate that implementation of the Settlement agreement will:

1. Increase the total annual surface water supply available to CID irrigators; significantly increase the CID system's resiliency to dry years and minimize the chances of a priority call by CID.
2. Over time, reduce total depletions in the Roswell basin and increase baseflows to the Pecos River; and
3. Reduce the possibility of New Mexico defaulting on its Pecos River Compact obligations, and most likely result in credit over the long-term.

The PRDSS has proven to be a valuable tool for evaluating various actual or proposed management policies in the Pecos River basin.

REFERENCES

Carron, John. 2004. “Model Evaluation of the Adjudication Settlement Agreement”. Unpublished report prepared for the New Mexico Interstate Stream Commission. 23 pages.

Carron, John, Jim McCord, Ali Elhassan, Peggy Barroll, Tomas Stockton and Miguel Rocha. 2006. “ Pecos River Decision Support System: Tools for Managing Conjunctive Use of Surface and Ground Water Resources.” *Ground Water and Surface Water Under Stress: Competition, Interaction, Solutions.* Proceedings of the USCID Water Management Conference, October 25-28, 2006.

Liu, Beiling, John Carron, and Jim McCord. 2003. “Evaluating the Consensus / Adjudication Settlement Plan: Application of the Pecos River Decision Support System”. *Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future. Peggy S. Johnson, Lewis A. Land, L. Greer Price, and Frank Titus, Eds.* Decision-Makers Field Conference 2003 New Mexico Bureau of Geology and Mineral Resources. pp. 112-115.

Thorson J. E., 2003. “The U.S. Supreme Court in an Original Jurisdiction Action *Texas v. New Mexico*, No. 65 Orig. (Pecos River)”. *Water resources of the Lower Pecos Region, New Mexico: Science, Policy, and a look to the future*. *Peggy S. Johnson, Lewis A. Land, L. Greer Price, and Frank Titus, Eds.* Decision-Makers Field Conference 2003. New Mexico Bureau of Geology and Mineral Resources. pp. 47-51.

COLLABORATIVE SOLUTIONS TO COMPLEX PROBLEMS: A PECOS RIVER BASIN, NEW MEXICO CASE STUDY

Elisa Sims[1]
Coleman Smith[2]

ABSTRACT

The Pecos River, a tributary of the Rio Grande, flows through eastern New Mexico for 500 miles and across four dams until it reaches the New Mexico-Texas state line south of Carlsbad, NM. The complex river system gains flows from snowmelt, flood inflows, and groundwater base inflow. The Pecos River Basin provides water to three irrigation districts, two of which rely primarily on surface water flows; the third pumps groundwater for irrigation. The New Mexico Interstate Stream Commission and the Office of the State Engineer (NMISC/OSE) are the primary state agencies jointly charged with water resource management in the basin.

One of the most important legal constraints on the system is the Pecos River Compact, which was ratified by New Mexico and Texas and approved by the U.S. Congress in 1948. Additionally, the fully appropriated basin is not completely adjudicated, adding additional legal stresses. To further complicate the basin's legal setting, the Pecos River is home to a federally threatened species of fish, the Pecos bluntnose shiner. As a result of the complex hydrologic conditions and legal constraints present in the Pecos River Basin, the NMISC/OSE has responded in innovative ways to provide solutions for meeting the water demands of various stakeholders in the basin.

The State has served as a facilitator, to bring numerous stakeholders with varying interests together to negotiate a settlement to a long-standing adjudication suit. To support the settlement process, the NMISC/OSE created a suite of models known as the Pecos River Decision Support System (PRDSS), which models the complex hydrology and river operations of the Pecos River system. As a result of the settlement, the agency is purchasing land and appurtenant water rights, the majority of which will be transferred to a large capacity well field, currently being constructed. These actions are intended to increase river flows and to prevent a priority call for Compact compliance. Additionally, the agency has become involved in Endangered Species Act and National Environmental Policy Act compliance activities, traditionally considered federal processes. Overall, the NMISC/OSE has been compelled to expand its role as water resource manager in

[1] Staff Hydrologist, New Mexico Interstate Stream Commission (NMISC)/Office of the State Engineer (OSE), Bataan Memorial Bldg., Room 101, PO Box 25102, Santa Fe, NM 87504; elisa.sims@state.nm.us
[2] Water Resource Specialist, NMISC/OSE; coleman.smith@state.nm.us

the basin in order to provide long-lasting solutions to the water conflicts on the Pecos River.

INTRODUCTION

The Pecos River is a typical western American desert river system surrounded by issues of complex hydrology, interstate/intrastate conflicts, endangered species law, and politics, that requires the State of New Mexico to take an atypical approach to water resource management compared to other river systems in the region. The purpose of this paper is to describe the setting that surrounds the Pecos River Basin and explain the steps that have been taken to balance the many competing needs that occur within the basin. Specifically, it is important to share with other water management agencies the approach the New Mexico Interstate Stream Commission and the Office of the State Engineer (NMISC/OSE) has taken to ensure that the necessary parties work together to develop long-lasting solutions to the basin's challenges.

Description of the Pecos River Basin

Geography: The Pecos River originates in the Sangre de Cristo Mountains, in north central New Mexico. From its headwaters, it flows 500 river miles through eastern New Mexico and captures 19,000 square miles of New Mexico drainage area. As it flows, the river crosses four dams, irrigates approximately 45,000 acres of farmland, passes through two sections of federally designated critical habitat, and finally crosses the New Mexico-Texas state line south of Carlsbad, New Mexico (Figure 1). Once across the state line, the river flows another 400 river miles to its confluence with the Rio Grande near Langtry, Texas.

The majority of the Pecos River Basin is categorized as desert or semi-desert. The average rainfall across the basin is 11-15 inches per year. In the southern portions of the basin, where much of the agriculture economy is located, average summer temperatures vary from the high 60s to low 100s.

Hydrology: The water supply in the Pecos River Basin is derived from three sources: snowmelt runoff from the northern mountains, flood inflows from summer monsoon events, and groundwater inflows. The annual snowmelt and runoff from the Sangre de Cristo Mountains has averaged 50,000-60,000 acre-feet per year over the last 30 years. The flood inflows are, on average, the largest source of surface water supply in the basin, but are also highly variable. The largest flood events have recorded hundreds of thousands of acre-feet. In other years, the lack of flood inflows coincides with the most significant drought periods in the basin. Intermittent flow conditions in the river during the summer months are not uncommon.

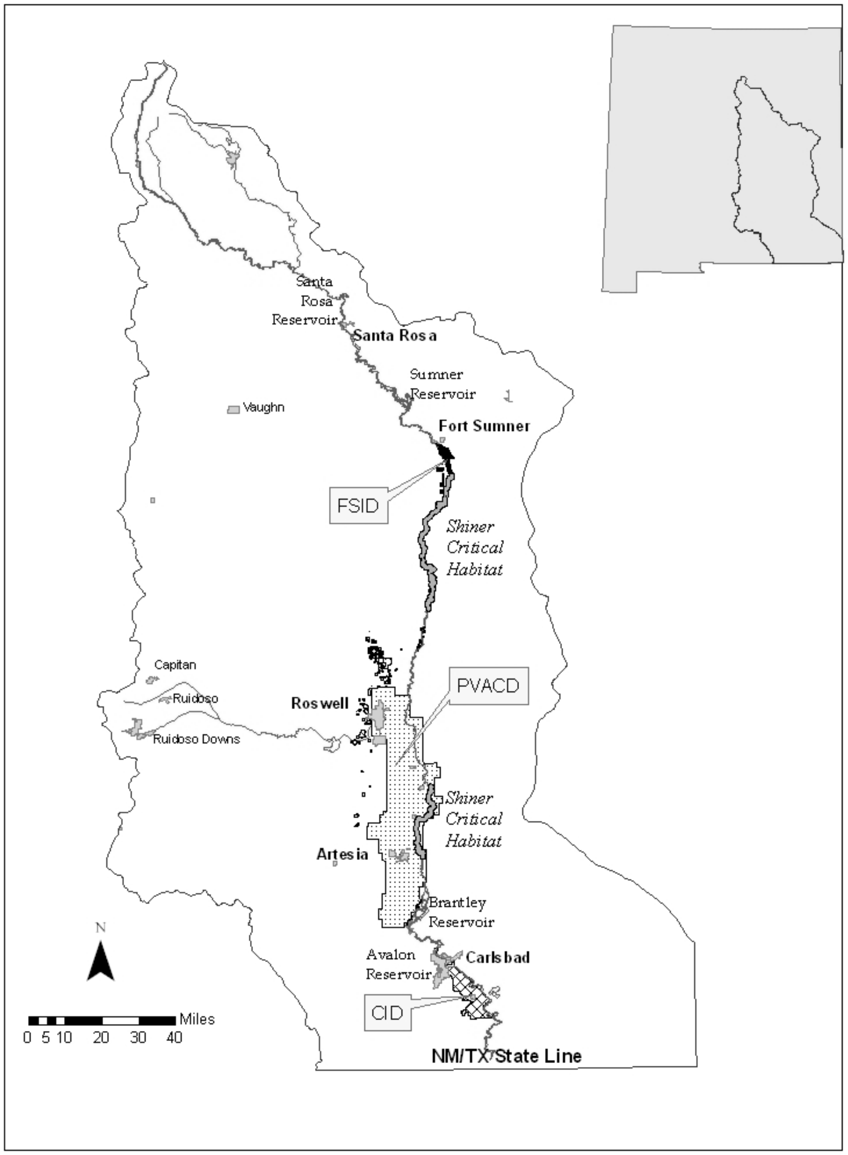

Figure 1: Map of Pecos River Basin, New Mexico

Groundwater inflow, or base flow, is an important contributor to the Pecos River's water budget. Base flows occur in three main locations along the river. The most northern source of base flow originates from the springs located near Santa Rosa, NM. These springs contribute 36,000-60,000 acre-feet annual to the river. Downstream, south of Roswell, base flow originates in artesian and shallow aquifers. This area is called the Roswell Artesian Basin (RAB) and is recharged by the mountains and tributaries to the west of the Pecos River. The base inflow from the RAB has been as high as 120,000 acre-feet and as low as 15,000 acre-feet (Longworth and Carron, 2003). The wide fluctuation in the base flow can be contributed to a groundwater-dependent agriculture economy developed in the region in the early 1900s. Continuing south, the final location of large base inflows occurs in the Carlsbad area, from the Capitan aquifer and agriculture return flow. Base flow from the Capitan aquifer has been largely eliminated due to groundwater diversions. The agricultural return flow typically provides 30,000 acre-feet to the Pecos River (id).

Key Stakeholders

NMISC/OSE: The New Mexico Interstate Stream Commission and Office of the State Engineer (NMISC/OSE) is charged with actively protecting and managing the water resources of New Mexico for beneficial uses by its people, in accordance with the law (NMISC Strategic Plan, 2004). Specifically, in the Pecos River Basin, the NMISC must comply with the Pecos River Compact, signed in 1948 by New Mexico and Texas, and the U.S. Supreme Court Amended Decree, issued in 1988. In 2001, the NMISC coordinated communications in the basin that resulted in the Carlsbad Project Settlement Agreement, signed in 2003 (Reclamation, 2006).

Federal Agencies: The Bureau of Reclamation (Reclamation) is the major federal stakeholder in the Pecos River Basin. Reclamation owns three of the four dams on the Pecos River. Reclamation is under contract with CID to store and deliver water for the purpose of irrigation. Reclamation, through the U.S. Department of the Interior, is a party to the Settlement Agreement. As the lead federal agency in the basin, Reclamation has the responsibility to consult with the U.S. Fish and Wildlife Service (FWS) on endangered species issues. The FWS is responsible for ensuring that other federal agencies plan or modify Federal projects so that they will have minimal impact on federally listed species and their habitats (Shipley, 2004).

Irrigation Districts: The Carlsbad Irrigation District (CID) has the most senior surface water storage right in the basin and is authorized to irrigate 25,055 acres of cropland. In 1976, the CID requested that the New Mexico State Engineer implement the doctrine of prior appropriation through a priority call. The request was not approved for several reasons: legal limitations due to a lack of adjudication and a determination of “futility”. The State Engineer determined that curtailing Upper Pecos junior surface water users and the slow response time of groundwater accrual to the river in the lower Pecos from curtailing junior groundwater users would not result in a significant increase to the CID surface water supply. The State Engineer determined that the priority call would ultimately reduce the water supply available to many users (Reynolds, 1976). To date, the CID has not withdrawn their request. The Pecos Valley Artesian Conservancy District (PVACD) irrigates nearly 100,000 acres and represents the groundwater users in the basin. PVACD is located upstream from CID and intercepts much of the groundwater flow that would otherwise reach the Pecos River and contribute to CID’s surface water supply.

LEGAL SETTING

A complex legal setting defines, to a large extent, how water is managed in the basin. Both federal and state constraints exist. Several of the more prominent laws are described below. In addition, a combination of State water law, including the doctrine of prior appropriation, various adjudications, State Engineer Orders and Decrees, and Active Water Resources Management define the Pecos Basin water use regulatory environment.

Pecos River Compact and Amended Decree

In 1947, New Mexico and Texas negotiated the Pecos River Compact (Compact), which was ratified by the U.S. Congress in 1948. In 1988, as a result of a lawsuit filed by Texas against New Mexico, the U.S. Supreme Court issued an Amended Decree (Decree), which appointed a federal River Master and established an accounting methodology to verify state line water deliveries. In addition, New Mexico was required to pay a $14 million fine for past Compact violations. As part of the Decree, New Mexico is required to meet its Compact obligation with the delivery of water; monetary compensation is not permitted. The State can over-deliver water in any single year and accrue a state line credit, however failure to deliver sufficient water such that a net shortfall occurs is a violation of the Compact and Decree. Since 1988, New Mexico has struggled with maintaining compliance with the Compact and Decree, which enjoins the State from defaulting on its annual obligation to deliver Pecos River water to the State of Texas. New Mexico’s failure to comply with the terms of the Compact and Decree could result in the federal government intervening to manage water operations on the river to ensure Compact compliance.

Water Resource Conservation Project (NMSA §72-1-2.2)

In 1991, the New Mexico Legislature recognized that a water shortage existed in the Pecos River Basin and that maintaining compliance with the Compact based upon natural flows of the river would be difficult. As a result, they drafted legislation to create a Water Resource Conservation Project (NMSA §72-1-2.2) and the NMISC began purchasing and retiring water rights and leasing water from farmers in the basin. The leased water is used specifically for state line delivery to maintain compliance with the Compact, while the purchased water is retired to increase river flows.

NEPA

The National Environmental Policy Act (NEPA) of 1969 requires federal agencies to evaluate and publicly disclose the environmental effects of any “major federal action” prior to making a decision to proceed with that action. The environmental evaluation is usually documented in an Environmental Assessment (EA), or less commonly an Environmental Impact Statement (EIS). NEPA encourages federal agencies to coordinate and cooperate with state and local governments when a major federal action is contemplated to occur within their jurisdiction. Due to the Pecos River Compact and Settlement Agreement, almost any major federal action related to water resource management that occurs within the Pecos River Basin prompts the involvement of the NMISC/OSE.

ESA

The Endangered Species Act (ESA) of 1973 mandates all Federal agencies to protect threatened and endangered species and preserve their habitats. Agencies must use their authorities to conserve listed species and make sure their actions do not jeopardize the continued existence of a listed species (Shipley, 2004). The Pecos River Basin contains many federally threatened and endangered species. Those species most often involved in the Pecos water management discussion include: the Pecos bluntnose shiner (shiner) (*Notropos simus pecosensis*), Interior least tern (*Sterna antillarum athalossos*), Pecos assiminea (*Assiminea pecos*), Noel's amphipod (*Gammarus desperatus*), Roswell springsnail (*Pyrgulopsis roswellensis*), Koster's springsnail (*Tryonia kosteri*), and the Pecos sunflower (*Helianthus paradoxus*). All seven of these federally protected species are dependent on water resources in some way. The shiner lives in the mainstem of the Pecos and can be negatively affected by Pecos river operations. The Interior least tern is a bird species that has recently nested within the conservation storage space of Brantley Reservoir. The Pecos assiminea, Noel's amphipod, Roswell springsnail, and Koster's springsnail are invertebrate species that occur at sinkholes, springs, and associated wetlands near the Pecos River. The Pecos sunflower is dependent on wetland areas near spring seeps and cienegas.

SOLUTIONS

Consensus Plan and the Carlsbad Project Settlement

In the summer of 2001, the NMISC/OSE announced that the potential for a delivery shortfall at the state line existed. The proposed response to this situation was the implementation of priority administration. Under priority administration, water right holders would have their water usage involuntarily curtailed until Compact delivery requirements are met. To consider alternative measures, the NMISC/OSE facilitated the creation of an *ad hoc* committee comprised of representatives from local governments, industries, and agriculture who were charged with creating both short and long-term solutions to the ongoing issues associated with complying with the Compact and Decree. Formation of the *ad hoc* committee was monumental in itself. Many of the members and the entities they represented had long-standing disputes over water issues.

The committee reached a consensus to resolve both interim and permanent issues regarding Compact delivery obligations (Consensus Plan) (LPRBC, 2002). The

Consensus Plan and a budget request were presented to the New Mexico Legislature. The resulting legislation, NMSA §72-1-2.4, was based, in part, upon the resolutions of the Consensus Plan; additional requirements were established and the program was partially funded. Key components of the statute are: 1) purchasing farmland and appurtenant water rights of varying amounts in the Carlsbad, Roswell, and Ft. Sumner areas, 2) settling a 50-year old lawsuit, known as the Lewis Adjudication, between the CID and PVACD, prior to any purchases, with contractual agreement between all parties, and 3) establishing priority of purchases (King and Sims, 2005). Elements from the statute were incorporated into the Carlsbad Project Settlement Agreement (Settlement).

The U.S. Department of the Interior, State of New Mexico, NMISC, CID, and PVACD entered into the Settlement in early 2003. At its core, the Settlement resolves a long-standing adjudication lawsuit in the Pecos Basin between the CID and PVACD. The Settlement has three primary components: 1) Entry of a Partial Final Decree (PFD), 2) Implementation of the Consensus Plan, and 3) Completion of Federal NEPA compliance activities. The PFD judicially establishes the allowable annual diversion and storage rights of the United States and the CID, and CID's right to deliver water for members of the CID (State of New Mexico, 2003). The Consensus Plan requires the State to purchase a minimum of 4,500 acres of land and water rights in the CID and 7,500 acres of land and appurtenant senior artesian water rights in the RAB. Full implementation of the Settlement requires the purchase and retirement of 18,000 acres and appurtenant water rights. Additionally, the Consensus Plan requires the NMISC/OSE to develop an augmentation well field capable of producing 15,750 acre-feet of water annually to the river to supplement CID water supply, and aid in meeting Compact delivery obligations. All acreage amounts established by the Consensus Plan were negotiated by the Settlement parties. These amounts were modeled using the decision-making tools (described in the PRDSS section below), found to be acceptable, and were finalized, before signing the Settlement. Finally, as part of the Settlement, the State is required to complete two environmental impact statements, described below.

The New Mexico Legislature has partially funded the Settlement. To date $66.5 million have been appropriated for implementation. It is estimated that an additional $30 million is required for full implementation. The State has acquired 2,350 acres in CID, and 4,138 acres in RAB all with appurtenant water rights. NMISC/OSE has developed the full augmentation well capacity, however pipeline delivery infrastructures are still being constructed. The well field project has also been supported by a $1 million grant (State matching funds required) from the federal Water 2025 Program.

NEPA

Currently, the NMISC/OSE is jointly leading the development of two Environmental Impact Statements (EIS) with Reclamation. Completion of the EIS documents will satisfy one component of the Settlement.

Carlsbad Project EIS: The Carlsbad Project Water Operations and Water Supply EIS involves the federal action of modifying river operations between Sumner Reservoir and Brantley Reservoir to provide water for the shiner. Historically, Reclamation has operated the dams on the Pecos River to maximize the delivery efficiency of irrigation water for use by CID. This method of controlling flow in the river has resulted in river drying during hot, dry summers. The section of the river that is most susceptible to drying has been classified by the FWS as critical habitat for the shiner. The Carlsbad Project EIS attempts to strike a compromise between the needs of CID and the needs of the shiner. NMISC/OSE is involved in NEPA process to ensure 1) the State's interests in the Pecos River Compact are protected, 2) the modified river operations do not result in new depletions, and 3) the Settlement is not compromised.

Long Term Miscellaneous Purposes Contract EIS (LT MPK EIS): The NMISC/OSE and Reclamation are jointly preparing the LTMPK EIS to evaluate the environmental impacts of entering into a long term contract that converts Carlsbad Project water from irrigation purposes to purposes other than irrigation, specifically state line delivery. This contract would enable the state to take delivery of its portion of the annual allotment of Project water and any water that it may lease from CID members and release it to the state line. Under the contract, the State will have the ability to divert up to 50,000 acre-feet annually for state line delivery, for a term of 40 years.

ESA

Over the last five years, the NMISC/OSE has become more involved in conservation efforts related to federally threatened and endangered species. Traditionally, it is the role of the FWS and the NM Department of Game and Fish to undertake research and monitoring activities to conserve special status species on the state level. Due to potential impacts of species conservation efforts on the Pecos River Compact, the Settlement Agreement, and existing water rights, the NMISC/OSE has been compelled to become a more active participant in these ESA discussions and activities, as they relate to the Pecos River Basin.

One approach the NMISC/OSE has taken is to obtain legislative funding to conduct unique research activities on the river to determine the habitat and stream flow needs of the shiner. For example, in 2004, the agency funded an "egg drift" study that evaluated the amount of egg retention between Sumner Reservoir and Brantley Reservoir during a routine release of water for irrigation (called a block release). The purpose of the study was to determine if block releases were affecting the ability of the shiner to survive in the main stem of the Pecos River (Kehmeier and Medley, 2004). The project resulted in a determination that block releases, when kept to certain duration, did not constitute a threat to the shiner. It was also determined that management activities should focus on shiner habitat protection instead of block release regulation.

The NMISC/OSE has also taken steps to investigate the idea of re-introducing the shiner into other reaches of the river within the fish's historical range. The agency plans to be actively involved in the recovery planning process with the FWS in the near future. The NMISC/OSE understands that in order to regain the flexibility in water management on the Pecos River, the recovery of the shiner is necessary.

PRDSS

In response to the many conflicts and challenges in the Pecos River Basin, the NMISC/OSE developed a suite of hydrologic models referred to as the Pecos River Decision Support System (PRDSS). The PRDSS includes a RiverWare surface water model of the Pecos River, two groundwater MODFLOW models – the Carlsbad Area Ground Water Model (CAGW) and Roswell Artesian Basin Ground Water Model (RABGW), the Red Bluff Accounting Model (RBAM), and a Data Processing Tool (DPT). The models are based on the best available scientific data and standard, widely accepted methods. The PRDSS has been used extensively to evaluate the effects of potential modified river operations and the effects of the Settlement.

The PRDSS has been a valuable decision-making tool for quickly modeling and evaluating the outcomes of various agreements and policies implemented in the Pecos River Basin without waiting years to observe the physical results of management decisions. The NMISC/OSE sees the PRDSS as another step the state agency has taken to ensure that the state's interests are protected and the Compact obligations are met. The PRDSS is an important tool that provides technical information to decision makers to guide their management strategies.

SUMMARY

The NMISC/OSE has taken the steps necessary to ensure the Pecos River Basin stakeholders work together to develop long-lasting solutions to the basin's water resource challenges. These proactive steps have required the State to redefine its role from traditional water resource management agency to facilitator with other federal and state agencies. The State is continually challenged with finding the optimal solution to the many competing demands on the Pecos water supply including the needs of endangered species, irrigation districts, and federal Compacts. The ongoing activities in the Pecos Basin are representative of the types of activities currently being managed by the NMISC/OSE throughout the State.

REFERENCES

Bureau of Reclamation and New Mexico Interstate Stream Commission. (2005). *Long-term Miscellaneous Purpose Contract Draft Environmental Impact Statement* (Statement Filing Number: DES 05-59). Washington, DC.

Kehmeier, J., Medley, N. (2004). *Assessment of Pecos Bluntnose Shiner Egg and Larval Drift Potential in the Pecos River, New Mexico*. NMISC Report.

King, R and Sims, E. (2005). *Solving Water Needs in the Pecos River Basin* (pp.26-27, 31). Southwest Hydrology, Volume 4/Number 4.

Longworth, J., Carron, J. (2003). Water Resources of the Lower Pecos Region, New Mexico: Science, Policy, and a Look to the Future. *Surface Water Hydrology of the Pecos River* (pp. 20-27). New Mexico: NM Bureau of Geology and Mineral Resources.

Lower Pecos River Basin Committee. (2002). Resolution of the ad hoc Pecos Basin Committee January 16, 2002, Santa Fe, New Mexico. Unpublished.

New Mexico Office of the State Engineer. (2004). *Strategic Plan*. NMISC Report. Santa Fe, NM.

Reynolds, Steve E. (1976). Memorandum: Pecos River System Administration July 12, 1976. New Mexico Office of the State Engineer.

State of New Mexico. (2003). Partial Final Decree, *State of New Mexico ex. rel. State Engineer v. L.T. Lewis*, Nos. 20294 and 22600 Consolidated.

The Shipley Group, Inc. (2004). *Overview of the Endangered Species Act*. [Brochure]. Woods Cross, UT.

DEVELOPMENT OF REPLACEMENT WATER SUPPLIES BY THE LOWER ARKANSAS WATER MANAGEMENT ASSOCIATION

Thomas A. Williamsen[1]

ABSTRACT

The Lower Arkansas Water Management Association (LAWMA) was formed in 1973 as a "membership" association for the primary purpose of providing replacement water to allow its members to operate their wells under the rules and regulations enacted by the State Engineer. The purpose evolved somewhat by the rulings of the Special Master and U.S. Supreme Court in Kansas v. Colorado to also include the development of a program to replace well depletions both to Colorado surface water rights and to usable flow at the Colorado-Kansas Stateline in compliance with Colorado law and the Arkansas River Compact. In 1998, LAWMA re-organized as a non-profit corporation and issued stock to its members. LAWMA has purchased direct flow and storage water rights at a cost basis of value cost of $8.75 million and fallowed 8,283 acres of surface water irrigated farms to develop a water rights portfolio so that its members could continue to use their wells. LAWMA also has executed management agreements wherein members put up the water rights and LAWMA incorporates those water supplies with LAWMA's other water supplies to replace depletions caused by members' wells. The paper describes how LAWMA obtained and pooled the water supplies in order to replace the depletions caused by its members' well pumping.

INTRODUCTION

Irrigation canal construction began in the 1870s in the Arkansas River basin in southeastern Colorado. These early canal systems appropriated most of the available stream flow, so the later ditch builders constructed storage reservoirs to regulate the stream flows exceeding the direct flow demands. Even with the reservoir storage, the irrigation demands usually exceeded available supplies.

The Arkansas River Compact was negotiated by representatives from the states of Colorado and Kansas and was enacted by Congress in 1949. John Martin Dam was completed by the Corps of Engineers in 1948 and became a key element of the Compact. John Martin Reservoir is located on the Arkansas River 58 miles west of the state line. It currently has a conservation and recreation pool capacity of 348,683 acre-feet and flood control storage of 259,562 acre-feet (ARCA 1993).

In the 1950s and 1960s, high capacity irrigation wells were constructed in the valley-fill aquifer of the Arkansas River to supplement the surface water supplies

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[1] President, Helton & Williamsen, P.C., 384 Inverness Parkway, Suite 144, Englewood, CO 80112; twilliamsen@helton-williamsen.com.

and to irrigate additional land. The development of irrigation wells went largely unchecked until the “Water Rights Determination Act of 1969” was enacted by the Colorado legislature. This required that wells be included into the appropriation system so well owners had to register their wells with the State Engineer and obtain a decree from the District Court establishing a priority date, use, diversion rate and place of use. Since the water rights for the wells are junior in priority to the surface water diversions, the State Engineer enacted rules governing the use of the wells in 1973 (State Engineer 1973).

The Lower Arkansas Water Management Association, LAWMA, was formed in 1973 as a “membership” association for the primary purpose of providing replacement water to allow its members to operate their wells under the 1973 Rules. LAWMA’s mission has expanded in response to the rulings of the Special Master and U.S. Supreme Court in Kansas v. Colorado, No. 105, Original to also include the development of plans to replace depletions caused by well pumping both to Colorado senior surface water rights and to usable flow of the Arkansas River at the Stateline in compliance with Colorado law and the Arkansas River Compact. In 1996, the State Engineer amended the Rules and required that the well users annually submit for approval a “Rule 14 Plan” which identifies the amounts of allowable pumping, the resulting depletions, and the sources of water used to replace the depletions (State Engineer 1996a). The State Engineer also issued Measurement Rules in 1994 and amended in 1996 that require wells be metered or measured indirectly by use of power consumption coefficients (State Engineer 1996b). The Measurement Rules include verification procedures and standards required to assure the accuracy of the measurement device.

In 1998, LAWMA re-organized as a non-profit corporation and is now operated in a manner similar to a typical Colorado mutual ditch company. Replacement water is delivered to the Arkansas River to make up or replace the depletions to the stream flow caused by pumping the wells. LAWMA has issued 18,934 shares of common stock to its members. LAWMA’s purchases of direct flow water rights and storage, leases of water rights, and operational agreements have been pooled to allow its membership to continue use of their irrigation wells while developing a marketable asset that can be used for other purposes.

SETTING

The Arkansas River originates in the central Rocky Mountains near Leadville and runs southeasterly through Colorado to Kansas. The drainage area at the state line totals about 25,000 square miles. LAWMA’s primary service area is the Arkansas River main stem below John Martin Reservoir in Bent and Prowers Counties, but it has members above John Martin Reservoir near La Junta and Las Animas and in the tributary areas of Big Sandy Creek and Two Butte Creek. LAWMA’s headquarters are located in Lamar, the largest city in the area with a population of 8,500, an elevation of 3,600 feet and average annual precipitation of 12 inches.

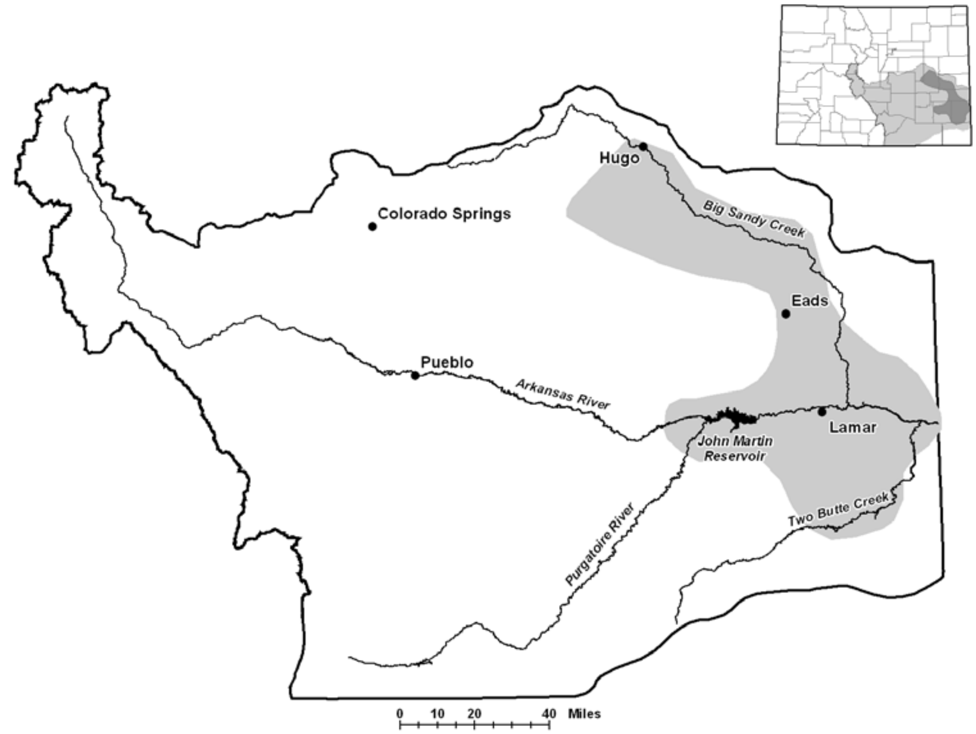

Figure 1. General Location Map Showing LAWMA's Service Area

The economy of the area derives largely from agriculture. The principal irrigated crops include alfalfa, corn for grain and silage, grain sorghum and onions. Dry land crops include winter wheat and sunflowers. There are several large beef feed lot operations, the largest being the Colorado Beef facility near Wiley. Also several swine confinement feeding operations started in recent years.

LOWER ARKANSAS WATER MANAGEMENT ASSOCIATION

LAWMA's powers and authorities are set forth in its Restated and Amended Articles of Incorporation and Bylaws. A seven-member elected board of directors (currently all seven are farmers) controls and manages the business and affairs of LAWMA. In general, the amount of replacement water provided by LAWMA to each shareholder member is directly proportional to the number of shares of common stock owned by the shareholder member which then converts to a volume of pumping by the shareholder's wells. Shares can be sold and transferred upon approval of the board of directors to different farm units or changed to a different use such as for wells used for industrial or municipal purposes.

For non-shareholder members, the rights and obligations relating directly to augmentation of the wells and other structures owned or operated by those members are established by written contract between the non-shareholder members and LAWMA. To provide a permanent replacement supply, the non-shareholder members will exchange water rights for shares issued by LAWMA according to a predetermined exchange formula.

Description of Member Wells and Other Structures

For its 2005 Rule 14 Plan, LAWMA included 520 wells that were in use prior to 1986. Further broken down by use, 476 wells were used for irrigation, 31 wells were used for municipal purposes, and 13 wells were used for commercial purposes. Of the irrigation wells, 299 wells supplemented water deliveries by ditch companies and 177 wells were the sole sources of irrigation water.

Change of Water Rights and Plan for Augmentation

In December 2002, LAWMA filed with the Water Court for Colorado Water Division No. 2 an application to: 1) change the use of its water rights from irrigation purposes to augmentation and replacement of depletions caused by wells and other structures used for irrigation, domestic, commercial, municipal, industrial, livestock, fish, wildlife, recreation, power generation and other uses and 2) adjudicate a plan for augmentation. The changed water rights will be used in the Rule 14 Plans and in the plan for augmentation.

LAWMA’s plan for augmentation is a procedural description or plan of how a well or structure developed after 1985 may continue to operate against the priority system by replacement of its depletions. Typical post 1985 uses include: 1) industrial and commercial uses such as gravel pits, concrete batching facilities, oil and gas production facilities, beef feed lots, swine confinement production facilities, and truck washes, 2) municipal and rural domestic water systems, 3) irrigation of the school grounds and athletic fields, cemeteries, parks, and agricultural crops, and 4) fish, wildlife, and recreation uses. In some cases the members have purchased LAWMA shares or assigned water rights to LAWMA to cover the depletions. LAWMA combines the water yields of the assigned water rights with its yields from direct flow and storage water rights and then distributes the combined replacement supplies as needed to replace the depletions. When the pending case is finally adjudicated, LAWMA will annually submit to the State Engineer a projection of the depletions for the users covered by the plan for augmentation and a schedule of the replacement deliveries.

Colorado law required LAWMA to provide notice to other water users in the Arkansas River basin of its intent and to allow others to participate in adjudicating the case. There were 18 parties that submitted statements of opposition to LAWMA’s case. Terms and conditions were developed and negotiated with the objectors to resolve potential injury issues such as determination of depletions, timing and amounts of historical return flows, volumetric limitations on the use of the changed water rights, measurement, accounting, dry-up, re-vegetation of fallowed fields and others. Settlement negotiations were successful and stipulations were executed with all objectors. The State Engineer, as an objector, tentatively approved a stipulation pending comments to the proposed decree from Kansas. Two other objectors tentatively approved a stipulation pending the State Engineer's suggestions for incorporating Kansas' comments in the final decree. By settlement with objectors, LAWMA avoided a three-week long trial before the Water Court in April 2006. When the pending stipulations are executed, LAWMA will ask the Water Court to enter a decree that incorporates the terms and conditions negotiated with objectors.

WATER RIGHTS ACQUISITIONS

Since 1989 LAWMA has purchased direct flow water rights in one irrigation ditch located upstream and five irrigation ditches downstream of John Martin Reservoir. Under the Arkansas River Compact, water is stored in John Martin Reservoir during the non irrigation season and during times when the inflow exceeds downstream demands. The storage water is distributed into "Article II Accounts", 40 percent to Kansas water users and 60 percent among 9 Colorado ditches located downstream of John Martin Reservoir (ARCA 1980). Water from the accounts is released on demand of the owner to supplement the direct flow diversions during the irrigation season. LAWMA's full ownership of three and partial ownership of two Article II Accounts provides carryover supplies to balance the yearly fluctuations in the water supplies available under the direct flow water rights. Combining the storage water with the direct flow sources provides considerable flexibility in meeting the replacement needs of its members. Pertinent details of LAWMA's water rights acquisitions follow and also are summarized in Table 1.

Table 1. LAWMA's Water Rights Acquisitions

Canal	Purchase Year	Dry-up (acres)	Cost
Sisson-Stubbs	1989, 2006	480	$697,000
Manvel	1993, 1996	392	$662,000
Fort Bent	1994, 2001, 2004	84	$204,000
X-Y	1996	3,488	$1,950,000
Highland	1997, 1998, 2001	2,867	$2,970,000
Keesee	2004	972	$2,270,000
	TOTAL	8,283	$8,753,000

Note: The Sisson-Stubbs cost includes the value of 354 LAWMA shares at $1800 per share + $60,000 cash paid to the seller. The Fort Bent acquisition cost in 2004 includes the value of 85 LAWMA shares at $1800 per share traded to the seller.

LAWMA financed $7.963 million through low interest (2-3 percent) loans from the Colorado Water Conservation Board (CWCB). The indebtedness works out to $421 per LAWMA share.

The X-Y Ranch purchase requires further explanation because it was the only water rights acquisition that included a substantial block of land. In 1996, LAWMA purchased most of the 5,500-acre X-Y Ranch, 67 cfs out of 69 cfs of the direct flow water right for the X-Y Canal and all of the X-Y/Graham Article II Account. The irrigated acreage totaled 3,488 acres. The Colorado Division of Wildlife (CDOW) purchased about 3,300 acres, re-vegetated it and developed the X-Y Ranch State Wildlife Area. As part of the sale to CDOW, LAWMA agreed to replace the depletions caused by up to 1,475 acre-feet of well pumpage which is used to irrigate up to 676 acres of wildlife feed plots and to fill shallow ponds during fall migration. The remainder of the land was sold without water rights. LAWMA's net cost of the water rights was $1,950,000.

Leases and Contractual Agreements

LAWMA has executed agreements with certain members who bring water rights to LAWMA in exchange for replacement water supplies managed by LAWMA under substitute water supply plans annually approved by the State Engineer. When LAWMA's plan for augmentation is approved by the Water Court, these users will be included in LAWMA's plan for augmentation. In general, LAWMA manages the water rights as part of its portfolio and accounts for the member's replacement needs. Replacement water exceeding the member's need is available for LAWMA's use. The yield of the water rights and limit on the member's use is based on the expected dry year yield of the water rights. Accordingly, LAWMA has use of the net excess in average and wet years for its members. The advantages to the member are an economy of scale because it is more efficient, water and dollar wise, to develop an umbrella-type plan for augmentation with a pool of water resources than to develop an individual plan for augmentation using a single source of augmentation supply. Descriptions of these agreements follow.

Five Rivers Ranches (formerly known as Colorado Beef): Five Rivers operates an 80,000-head capacity feed lot operation about 10 miles west of Lamar. They use alluvial wells to produce the livestock water and other water needed for operation of the feedlot. Five Rivers purchased the "West Farm" located just east of Lamar and the associated shares in the Lamar Canal and Irrigation Company. Five Rivers committed 3,477 shares (13.3 percent of the outstanding shares) and up to 999 acres of dry-up under the 1995 agreement.

Colorado Division of Wildlife (CDOW): CDOW operates a fish hatchery near Las Animas, upstream from John Martin Reservoir, and the Higbee State Wildlife Area east of Lamar. CDOW purchased the Lamar Canal and Fort Bent Ditch water supplies, represented by 4,720 Lamar shares (18.1 percent of the outstanding shares) and 401 Fort Bent shares (3.4 percent of the outstanding shares), from the owners of the "Center Farm". LAWMA included the CDOW shares in its change of water rights and included the Las Animas Fish Hatchery and other recreational facilities in the plan for augmentation. The water attributable to the shares will be delivered back to the Arkansas River through augmentation stations from both canals. LAWMA will use the delivered water in its Rule 14 Plans and the plan for augmentation and in return will provide replacement water for depletions caused by CDOW facilities within LAWMA's service area from LAWMA's pool of water rights. For this service, LAWMA retains 15 percent of CDOW's water supplies for use by LAWMA's members.

City of Lamar: The City of Lamar and LAWMA executed a memorandum of understanding in which LAWMA may use the City's 50 Lamar Canal and Irrigation Company shares and any of the City's water available under 1,316 shares of Fort Bent Ditch Company stock in amounts over and above the City's needs. The City has a well field in the Clay Creek basin (a tributary of the Arkansas River about 5 miles east of Lamar) that provides the City's potable water supplies. Water from the Fort Bent Ditch is delivered to a recharge site along Clay Creek to recharge the aquifer. LAWMA delivers the 50 Lamar shares back to the river through the augmentation station and when available the Fort Bent shares through an augmentation station. LAWMA changed the use of 923 shares of the City's Fort Bent stock and the 50 Lamar Canal shares from irrigation to include augmentation and replacement purposes for use in LAWMA's Rule 14 Plans and plan for augmentation. The City will further change the use to include recharge of the Clay Creek aquifer and other more specific uses in a separate Water Court application.

Other Agreements: LAWMA executed several management agreements and leases with commercial entities involving 764 shares of Fort Bent Ditch Company stock. Theses shares are part of LAWMA's change of water rights and plan for augmentation. The water available to 356 shares is delivered to the Arkansas River through the augmentation station of which 207 shares are used in substitute water supply plans for several commercial entities. The remaining 408 shares also can be used by CDOW for irrigation of wildlife feed plots at the Higbee State Wildlife Area. It is planned that these users will trade their Fort Bent shares for LAWMA shares, and their future depletions will be replaced under LAWMA's plan for augmentation.

OPERATIONS

Administration and accounting of the well pumping and stream depletions are broken down into two categories: 1) those wells with decreed water rights before 1986 and are administered under a Rule 14 Plan and 2) those wells and structures developed after 1985 and administered under substitute water supply plans approved annually by the State Engineer or under a plan for augmentation decreed by the Water Court. Annually since 1996, LAWMA has submitted a Rule 14 Plan to the State Engineer. The Rule 14 Plan describes the projected well pumpage by each farm unit and shows how LAWMA's water rights will be used to replace the depletions with respect to Colorado water users and to Kansas. The State

Engineer's staff reviews the Rule 14 Plan and then issues an approval, if acceptable, with conditions.

The board of directors sets the allocation to shares based on the projected yield of LAWMA's water rights and carryover storage. The allocation is the amount of replacement water in units of acre-feet per share based on the 1) use of the well, supplemental or sole source, 2) irrigation system, gravity or sprinkler, and 3) the number of shares. The allocation is converted to an allowable amount of pumping per well or farm unit. Figure 2 shows the actual amounts of well pumpage covered under the Rule 14 Plans.

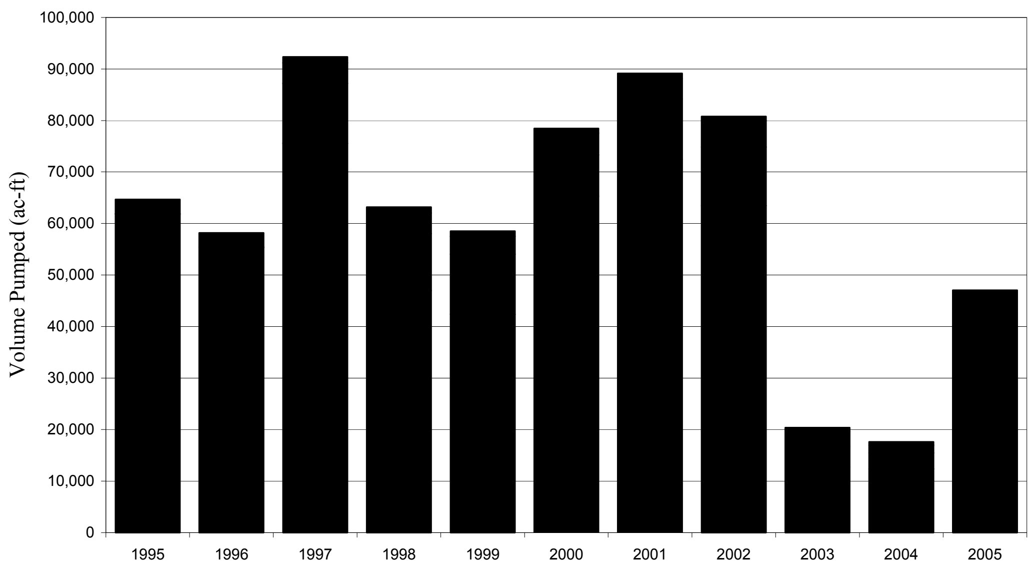

Figure 2. Annual Well Pumpage by LAWMA Members

The drought of 2002 reduced significantly the amounts of water available to some of LAWMA's replacement sources so LAWMA had to use most of its accumulated storage. The drought continued through 2003 and 2004 so the allocation was set much smaller in order to replace the depletions to the river caused by the earlier years' pumping and to accumulate storage. In retrospect, LAWMA should have been more conservative in the good water supply years so that there could have been more pumping in the drought.

Flow meter readings for those wells so equipped are submitted to LAWMA by the well owners monthly. LAWMA tabulates the readings and then submits the readings as a group to the Division Engineer, the State Engineer's administrative representative for the Arkansas River basin. Electrical power records are submitted by the power associations directly to the Division Engineer. For those wells relying on a power consumption coefficient (PCC), the pumping is calculated based on the supplied power record and the PCC for the particular well. The Division Engineer determines the consumptive use based on presumptive depletion factors and lags the depletion to the Arkansas River using response functions and user groupings.

LAWMA's replacement supplies from direct flow sources are quantified by stream flow gages located near the original points of diversion (Highland, Keesee, Manvel, X-Y and Sisson-Stubbs Ditches) or are delivered by the ditch company to the Arkansas River through designated augmentation stations (Fort Bent Ditch and Lamar Canal). LAWMA's Highland Canal water and LAWMA's Article II Account storage water can be bypassed or released from John Martin Reservoir to the river, as needed, to replace the depletions to Colorado ditches or can be transferred to the "Offset Account". This special account (ARCA 1998) was established to regulate replacement water delivered to John Martin Reservoir primarily for replacing depletions with respect to usable state line flow. Kansas can call for the water stored in the Offset Account at any time it is usable by Kansas. An annual charge of 500 acre-feet of fully consumable water (paid annually by LAWMA) for the first 10,000 acre-feet regulated in the account plus 5 percent of delivered water exceeding 10,000 acre-feet is solely for Kansas' use.

Monthly, LAWMA and the Division Engineer work together to coordinate the storage releases and transfers from LAWMA's storage water and to measure and record the direct flow deliveries so that the replacement water supplies match the stream depletions caused by LAWMA's members.

FUTURE

As provided in LAWMA's Bylaws, LAWMA is implementing a procedure to issue preferred stock to those members needing a non-curtailable source of augmentation water. Non-curtailable water uses include gravel mines, concrete batching facilities, beef and swine feeding operations, and other industrial and municipal uses for which the stream depletions are fairly constant from year to year. Additionally, such uses cannot reasonably or practically be curtailed. In operation of the plan for augmentation each year, LAWMA will assign a predetermined yield to the preferred shares and then adjust the yield available to the common shares.

LAWMA, CDOW and the Colorado Division of Parks (CDP) have executed an option to purchase the remaining one-half of the Keesee Ditch water rights. The Keesee Ditch direct flow and Article II Account water would be used 9 years out of 12 years by CDOW and CDP to replenish the 15,000 acre-foot permanent pool in John Martin Reservoir. Maintenance of a permanent pool is important for recreation and fish and wildlife uses. LAWMA would select 3 dry years out of 12 years to use the water derived from the Keesee Ditch for replacement purposes under Rule 14 Plans and the plan for augmentation. The purchase price is $3.6 million of which LAWMA would pay $1.26 million. LAWMA will finance their cost by issuing and selling 400 shares of preferred stock at a price of $3,166 per share to its members. The Arkansas River Compact Administration must agree to allow CDOW and CDP to use the Keesee Ditch water for maintenance of the permanent pool. Discussions are ongoing with Kansas and Colorado officials about using the water for this purpose.

Tri State Generation is planning the construction of a major coal-fired power plant in southeastern Colorado and has begun purchasing water rights in the lower Arkansas River basin, including LAWMA shares. At this time it is not clear what role LAWMA will play in assisting Tri State with the development of a reliable water supply. But with LAWMA's storage supplies, varied portfolio of water rights and water management experience, LAWMA most likely will be involved.

CONCLUSIONS

Many water rights transfers from agricultural purposes to municipal and industrial uses in the Arkansas River basin involved transporting the water out of basin. LAWMA's water rights acquisitions have kept the water rights in the hands of the local users while developing marketable assets and making it easier to develop necessary water supplies for local economic development. LAWMA has been innovative and future thinking by pooling its water resources to efficiently and effectively provide water supplies to their members.

REFERENCES

Colorado State Engineer 1973. "Rules and Regulations Governing the Use, Control, and Protection of Surface and Ground Water Rights Located in the Arkansas River Basin", February 19, 1973.

Colorado State Engineer 1996a. "Amended Rules and Regulations Governing the Diversion and Use of Tributary Ground Water in the Arkansas River Basin, Colorado", June 4, 1996.

Colorado State Engineer 1996b. "Amendments to Rules Governing the Measurement of Tributary Ground Water Diversions Located in the Arkansas River Basin", February 28, 1996.

Arkansas River Compact Administration 1980. "Thirty-Second Annual Report Arkansas River Compact Administration, Appendix "C-1" Resolution Concerning an Operating Plan for John Martin Reservoir", 1980.

Arkansas River Compact Administration 1993. "Forty-Fifth Annual Report of the Arkansas River Compact Administration 1993 Compact Year", 1993.

Arkansas River Compact Administration 1998. "Stipulation Re Offset Account in John Martin Reservoir in Kansas v. Colorado, No. 105 Original", March 17,1997 and amended by "Resolution Concerning an Offset Account in John Martin Reservoir for Colorado Pumping", March 30, 1998.

INTEGRATED WATER MANAGEMENT IN THE BEAR RIVER BASIN

William H. Atkin[1]

ABSTRACT

The Bear River basin includes portions of Utah, Idaho and Wyoming and has the largest river in the Americas with no outlet to the ocean. There are water rights to the use of water from Bear River and its tributaries and decrees to distribute between users as well as an interstate compact to regulate between states. Central to the Bear River system is Bear Lake, which is operated as a reservoir to provide water for irrigation and to produce power. Utah Power, irrigators and Bear Lake interests signed a settlement agreement that allocates annual storage releases for irrigation. The power company and the compact states also memorialized historic operation by a signed agreement. Recognizing the interconnection between ground water and surface water, conjunctive management has become the policy of the states. The water rights, policies, decrees, compact and agreements form the foundation of the "law of the river" for Bear River.

Management of the Bear River within these constraints is understandably complex. Interstate delivery of natural flow and accounting of storage allocations below Bear Lake are cooperatively performed by the states using computer models. During the irrigation season, the weekly process of data collection and computer modeling of the river had resulted in a time delay between diversion and decision-making or regulation. Recent automation, however, using telemetered gages and meters has facilitated data collection and sharing, reducing delays and allowing more accurate monitoring and regulation. Through computer models and automated data collection and sharing, water management issues have become more manageable, and decision-making and regulation more timely.

INTRODUCTION

From its headwaters high in the Uinta Mountain range of Northern Utah, the Bear River travels 500 miles and crosses five state lines before entering into the Great Salt Lake, a mere 90 miles from its source (Figure 1). Midway along its course, the river is diverted into Bear Lake, a natural lake, whose level may be increased by as much as 21 feet to hold an additional 1.4 million acre-feet of usable storage. On the north shore of the lake is a natural dike and a pumping plant where stored water may be released into an outlet canal that returns water to the Bear River to produce power and provide supplemental irrigation water to 150,000 acres of cropland and pasture. The river basin above Bear Lake is known as the upper Bear River while the area below Bear Lake is referred to as the lower Bear River.

[1] Assistant Regional Engineer, Utah Division Of Water Rights, 1780 N. Research Pkwy, Ste. 104, Logan, UT 84341; willatkin@utah.gov.

Below Bear Lake, tributaries more than double the flow of the Bear River before it passes through the Bear River Migratory Bird Refuge and into the Great Salt Lake, never making it past the Great Basin to the ocean.

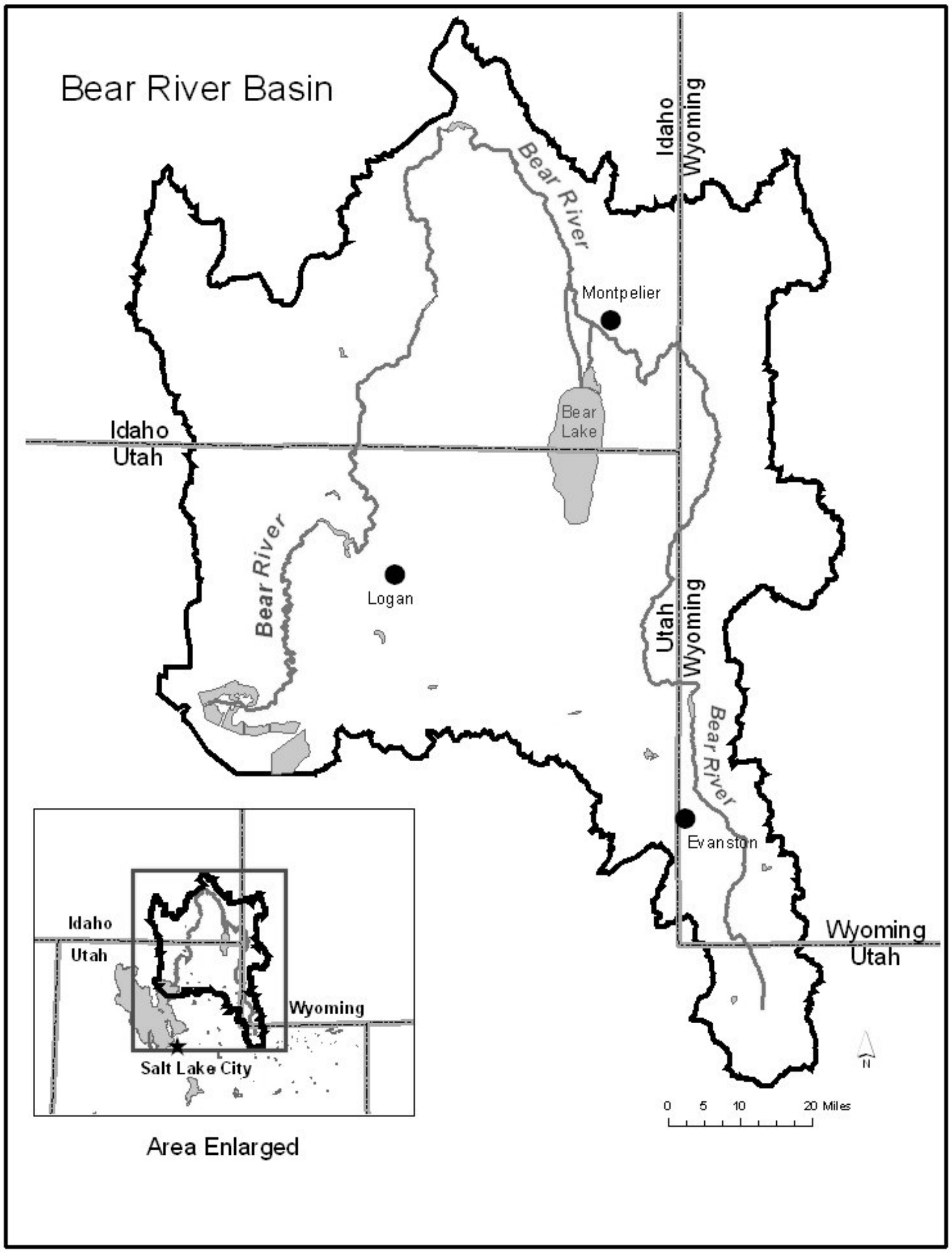

Figure 1. Bear River Basin

The Law of the River

The phrase, "Law of the River," is usually used in reference to the Colorado River with its interstate compact, but every river, to one degree or another, has a "law of the river." It may be as simple as the water rights to a small creek or as complex as interstate or international law on a river. The "law of the river" for Bear River is comprised of state water rights, an interstate compact, court decrees and mutual agreements.

Pioneers began diverting the Bear River in the late 1800s after tapping its tributaries. Several larger canals were constructed around the turn of the century. In 1909, the predecessors to Utah Power began the project that would divert water into and out of Bear Lake and generate power at hydroelectric power plants along the Bear River. Utah Power also bought Wheelon Dam from Utah and Idaho Sugar Co. (predecessor to Bear River Canal Co.) and filed on the hydropower rights. They agreed to deliver a total of 900 cfs to the two canals that head at what is now Cutler Dam, supplementing any deficiencies in natural flow with stored water from Bear Lake. Over time, all the major canals and small irrigation pump owners also signed contracts with the power company for storage water from Bear Lake[2].

In 1920 in Idaho and 1922 in Utah, water rights in the lower basin were adjudicated. The Dietrich Decree[3] is a federal decree in the state of Idaho and the Kimball Decree[4] was a state decree in Utah. The decrees quantified the usage and flow as well as the priority of the water rights to the Bear River and its tributaries. They also established travel times and transit losses for the storage releases from Bear Lake and allow Utah Power to operate the river in the instance of storage water as if the river were a canal. Of particular importance, the federal Dietrich Decree recognized the rights of Utah and Idaho Sugar Co. (Bear River Canal) in Utah and directs that the "…official charged with the administration of the decree, shall see that there is delivered at the Utah state line such quantity of water as is necessary, together with natural increment below said Utah state line, to satisfy said rights in accordance with their dignity and priority as herein recognized."

The Bear River Compact was signed in 1958 and amended in 1980 to regulate the distribution and development of the Bear River between the states of Wyoming, Idaho and Utah. Among other things, it provides a procedure for declaration of a water emergency, in which case water would be delivered by priority without regard to state boundary. The Bear River Commission is charged with the administration of the compact and authorizes an Engineer-Manager to oversee

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[2] Jibson, W. N., 1991, History of the Bear River Compact.
[3] Utah Power & Light Company vs. Last Chance Canal Company, Ltd., Et al.
[4] Utah Power & Light Company vs. Richmond Irrigation Company, Et al.

distribution between states. The individual states each have their own river commissioners to distribute water among users and report diversions.

For nearly a century, Utah Power has had a major influence on the operation of Bear Lake and Bear River. Originally, the hydroelectric power produced along the Bear River was the main source of power in the region. Storage releases from Bear Lake have also augmented late summer flows that have made the agricultural region more productive. As other sources of electricity have become available, the main focus of the Bear River system has become irrigation.

More recently, interests concerning Bear Lake other than agriculture and hydropower, such as recreation and environmental interests, have become more significant and a lawsuit challenging Utah Power's plan to dredge an existing channel in Bear Lake was filed. The power company argued that they needed the channel to efficiently pump their storage water when the lake was low during an extended drought. To resolve the matter, a settlement agreement was signed in 1995 by Utah Power, irrigation contract holders and groups and individuals representing other interests around Bear Lake. In the settlement agreement, the lawsuit was dismissed and irrigators agreed to allocate storage releases for irrigation annually, based on forecasted lake levels. By reducing allocations during extended periods of drought and low lake levels, water is reserved for lake recovery. Another key element in the settlement agreement was the acceptance of interstate distribution, by priority, circumventing the need to petition the Bear River Commission for an official declaration of a water emergency.

In 2000, Utah Power signed an operational agreement with the basin states to memorialize its historic operation of Bear Lake. It agreed to only release storage from Bear Lake to fulfill its irrigation contracts or for flood control and generate power at downstream hydropower plants as a secondary benefit.

Groundwater – Surface Water Interaction

As the compact states were grappling with administration of the decrees, compact and agreements, the issue of dealing with the effect of groundwater on the Bear River always came up. Certainly, a call on the river would have to consider groundwater impact and the states were committed to addressing it. To that end the Bear River Commission requested the states of Utah and Idaho investigate the impact of groundwater development and that the Commission's Technical Advisory committee review their findings[5].

The US Geological Survey, in a report on the hydrology of Cache Valley[6] identified the interconnection of the surface water and ground water systems and

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[5] Bear River Commission, 2002.
[6] Kariya, K. A., M. D. Roark and K. M. Hanson, 1994.

created a groundwater flow model to simulate flow in the unconsolidated basin fill in that portion of the lower Bear River basin. The report found that there was generally a 1:1 relationship of groundwater depletion to surface water depletion in the Bear River basin. The state of Utah took the groundwater flow model and applied it on a monthly time step and analyzed where the depletions would occur. It found that much of the depletion would occur to tributary streams that were fully appropriated by senior rights, which could "dry dam" the tributary during water shortages. Below these senior tributary diversions, the impact to the main stem of the Bear River in Utah, on the average, is only 4.1 cfs. Similarly, Idaho found that their impact to the main stem of the Bear River is only 4.9 cfs. The total estimated average depletion of 9.0 cfs is less than one percent of the average annual discharge at the Idaho-Utah state line, smaller than an acceptable measurement error. The resulting decision was to not include groundwater in the interstate accounting and distribution of the lower Bear River.

Because of the need to conjunctively manage groundwater to protect surface water rights, the State Engineer in Utah adopted an Interim Groundwater Management Plan for Cache Valley[7] in 1999. In 2001, the Director of the Idaho Department of Water Resources similarly created a Ground Water Management Area[8] to protect surface water rights and limit new groundwater development.

MANAGEMENT

There is an axiom that if you want to manage a resource, you must first measure it. The flows of the Bear River have been measured and records kept for close to 100 years by the USGS and by Utah Power. There are also records of diversions by some of the major canals that have been kept for almost as long. Lately, records of diversions by smaller diversions and pumps have also been kept. Interstate computer models have been developed and used for the past 15 years to distribute natural flow and account for storage diversions.

Data Collection

To properly distribute and manage the operation of the Bear River system, the river commissioners in each state collect diversion data weekly. This data is cooperatively shared between states and includes canal diversions and pump diversions. In addition to the five major canals, there are over 90 pumps and small diversions in Utah and close to 30 in Idaho. Measurements of river flows and reservoir contents are reported by Utah Power and the USGS and are obtained by the river commissioners as well.

[7] Utah Division of Water Rights, 1999.
[8] Idaho Department of Water Resources, 2001.

In the upper Bear River, above Bear Lake, diversions are reported by the river commissioners to the Engineer-Manager of the Bear River Commission who administers provisions in the compact to distribute between states if there is a call on the river. For the lower Bear River, the diversion, reservoir and stream flow data are input to computer models that facilitate distribution between users.

Interstate Modeling and Delivery

Both Idaho and Utah have computer models to perform the interstate distribution of the Bear River below Bear Lake. Each state has their own operating system and the models are separate and distinct but conceptually and realistically the same. The redundancy also provides a check on operation. The general approach is a reach-gain analysis to determine natural flow available and a distribution by priority of that natural flow with deficiencies made up by storage water. Following is a description of the Utah model.

The Lower Bear River Distribution Model (LBRDM) is a daily accounting model that utilizes WATMODEL[9], a water accounting software model developed by the Utah Division of Water Rights. WATMODEL facilitates the handling of numerous diversion sets over the length of a river. Each diversion variable represents an array of daily values. The river may be divided into reaches with reach variables that are connected such that a diversion in one reach will affect downstream reaches. WATMODEL also has functions that help in distribution, such as the "distribute" function that can take each diversion, in priority and effectively call water down from upstream reaches.

The natural flow reach-gain calculation for a reach is given by the following mass balance equation:

$$NF^{r} = Out - In + Div\ (+/-)\Delta Res + NF^{r-1} \quad (1)$$

Where: NF^{r} is the natural flow in a reach
Out is the measured flow leaving the reach
In is the measured flow entering the reach
Div is the diversions within the reach
ΔRes is the change in reservoir contents (+ storing, - releasing)
NF^{r-1} is the natural flow entering the reach.

The LBRDM utilizes the hydrologic factors decreed in the Dietrich and Kimball decrees. Transit losses and travel times were set for storage releases. From Bear Lake to Cutler Dam, transit losses were decreed to be a total of 4½% with 1½% in the first reach and an additional 1% in each reach down to Cutler Dam. For simplicity, the losses from the previous day are added in, rather than computed by

[9] Utah Division of Water Rights, 2005.

iteration. Similarly, travel time was decreed to be 24 hours in each reach, and is accepted to be 4 days from Bear Lake to Cutler Dam. A decreed adjustment for the natural gain of Bear Lake and Mud Lake is also in the model.

Reach-by-reach in downstream order, the gain is calculated and the natural flow is accumulated. Once the natural flow is determined in each and all reaches, it can be distributed, sequentially, by priority. WATMODEL reach variables, connected in downstream order, have the effect of distributing up and down the river, regardless of reach boundaries. When natural flow is distributed to a diversion it reduces the natural flow available in that reach and in downstream reaches. When the natural flow in a reach is all distributed, no more natural flow may be distributed in that reach nor in upstream reaches.

Decision-making and Communication

During the irrigation season stakeholders have bi-weekly conference calls to stay on top of the operation of the river. Utah Power has sponsored the calls and representatives of the irrigators, Utah Power and the states have participated. Information discussed in the conference calls includes reservoir levels, flow at gaging stations, available natural flow, storage releases, diversions and projected diversions. Decisions are then cooperatively made to maintain a "balance" on the river, balancing demands with resources. Coordinated management of the river system requires data sharing between stakeholders with the objective of efficient use of the resource.

Conference calls have proven to be valuable to the operation of the river. Utah Power has been able to coordinate decisions on storage releases based on projected diversions and "balance" of the river. Irrigators have been able to make decisions on diversions based on updated natural flow calculations. The states and their river commissioners have been able to provide information on river modeling and accounting and projections of regulation. This was evident during July and August of 2004 when storage allocations were greatly reduced, natural flow was limited by drought, and storage allocations were close to being used up.

DATA AUTOMATION

Although the data collection and river modeling by the states has greatly enhanced the management of the Bear River, there has been a time delay between diversion and regulation or decision-making. This posed a problem in 2004 when an irrigator on the lower Bear River refused orders of the State Engineer to curtail diversion. The river commissioner and state officials had to monitor and regulate his diversions at a remote location on a daily basis. Since then, automated data collection systems have been installed on both the upper and lower Bear River and similar systems are being installed in Wyoming and on major canals in the lower basin portion of Idaho.

Through a cooperative project with the US Bureau of Reclamation, an automated system of telemetered gages was installed in 2004 in the upper basin area of Utah. The data are displayed on the Bear River Basin web site[10]. Canals in Wyoming are now also automated and displayed at the same location. The monitoring and displaying of diversion data has made the jobs of the river commissioners for the states as well as the Bear River Commissioner Engineer-Manager easier and has proven beneficial for the irrigators as well. There have been times when interstate regulation has been unnecessary.

With the success in the upper Bear River basin in hand, attention was turned to automating the lower Bear River basin. Most of the system was installed and operational in the 2005 water year. Where the upper system used mostly gages in canals, much of the lower system includes meters on pumps.

The task of monitoring 93 pumps on the lower Bear River had proven to be time consuming and resulted at times, in delays and use of estimated data. With another grant from the Bureau of Reclamation, along with funding from the state legislature to provide the telemetry, irrigators paid to install meters on their pumps. Pressurized systems chose between ultrasonic meters and inexpensive on/off sensors on rated pumps. Flood systems chose between on/off float sensors and sonar sensors. Every effort was made to make an effective yet low-cost system. Each site also has a radio and an antenna to transmit diversion data to the central computer at the Logan Regional office of the Utah Division of Water Rights. All data storage is on the central computer and is displayed on the Division web site.[11]

CONCLUSION

As in many river basins, management of the Bear River within institutional constraints is complex. Like the string that holds the kite up in the wind, though, the institutions that form the "law of the river' have held water management up through some difficult drought cycles. Interstate delivery of natural flow and accounting of storage allocations below Bear Lake have been cooperatively performed by the states using computer models. Recent automation has facilitated data collection and sharing, reducing delays and allowing more accurate monitoring, regulation and operational river balance. Conjunctive management of groundwater and surface water has become the policy of the states and has resulted in limitations on additional groundwater development. Integrated water management using computer models, automated data collection and sharing and communication has made decision-making and regulation timelier, developing more trust and cooperation amongst competing interests.

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[10] www.bearriverbasin.org/canals

[11] http://waterrights.utah.gov/cgi-bin/dvrtview.exe

REFERENCES

Bear River Basin website www.bearriverbasin.org/canals

Bear River Commission, 2002, Report of the Technical Advisory Committee to the Bear River Commission Concerning Water Depletions Associated with Uses of Groundwater in the Lower Division, Salt Lake City, Utah.

Idaho Department of Water Resources, 2001, Bear River Ground Water Management Area, (available on-line at: http://www.idwr.idaho.gov/hydrologic/projects/gwma/br_gwma.htm

Jibson, Wallace N., 1991, History of the Bear River Compact, Bear River Commission, Salt Lake City, Utah (available on-line at: http://waterrights.utah.gov/techinfo/bearrivc/history.html).

Karya, K. A., D. M. Roark and K. M. Hanson, 1994, Hydrology of Cache Valley, Cache County, Utah and adjacent part of Idaho, with Emphasis on Simulation of Ground-water flow. Utah Department of Natural Resources Technical Publication No. 108.

Utah Division of Water Rights, 1999, Interim Cache Valley Ground-water Management Plan, (available on-line at: http://www.waterrights.utah.gov/wrinfo/mmplan/ugw/cachevly.pdf

Utah Division of Water Rights, 2005, WATMODEL unpublished software.

Utah Division of Water Rights, 2006, http://waterrights.utah.gov/cgi-bin/dvrtview.exe

Utah Power & Light Company vs. Last Chance Canal Company, Ltd., et al., in Equity No. 203, July 14, 1920.

Utah Power & Light Company vs. Richmond Irrigation Company, et al., February 21, 1922.

LOOKING FOR TROUBLE: ANTICIPATING IMPACTS OF CHANGING ALLOCATION OF IRRIGATION WATER

John D. Wiener, J.D., Ph.D.[1]

ABSTRACT

New forms of water transfer are beginning to appear, after decades of calls for increased flexibility in allocation as well as reduction of impacts from the traditional Western practice of "buy-and-dry" – moving water from farming to cities by ending irrigation forever on subject lands. Colorado's interest in improved water transfers increased with recent severe drought, continuing high growth rates of urban and ex-urban populations, and examination of needs for future water supply by the Statewide Water Supply Initiative (SWSI). Colorado does not want a state water plan, but has invested in improving water information and assessment of supply and demand. This study exposed potential shortfalls and may have accelerated competition for agricultural water. Colorado is experimenting with a water bank, but the first effort was severely limited in application and design, and normal agricultural innovation practices were not employed. Now, new forms are being developed in and out of the SWSI.

The Statewide Water Supply Initiative "phase 2" technical roundtables narrowed several issues, including alternatives to "buy-and-dry". Three basic additional kinds of water transfers appear to meet demands, and a small set of principles for water transfers are recommended. This paper reviews the three forms and the principles, and the presentation will report preliminary results from further inquiry into potential problems from use of the more flexible transfer forms. Anticipation of problems is desirable to maximize the certainty and predictability of new transfer forms, in order to help make them attractive compared to "buy-and-dry", and to more accurately compare costs and benefits and their distribution.

INTRODUCTION

The trend of water moving from agricultural uses in the West (National Research Council 2004, Western Water Policy Review Advisory Commission (WWPRAC) 1998) will continue, but how will these transfers take place, and with what impacts? Traditionally, irrigation water has been moved by permanent sale to cities. Some transfers included a few years of "lease-back" to farmers if the water was not presently needed. Eventually, water transfer decrees required that formerly irrigated lands not be re-watered. This is called, "buy-and-dry", and the local consequences are often severe due to loss of agricultural activity or sharp

[1] Research Associate, Environment and Society, Institute of Behavioral Science, University of Colorado, Boulder, CO, 80309-0468; John.Wiener@Colorado.edu

reduction if the land is converted to range or "dry-land" farming. Colorado's water law is among the most advanced in making water rights a fully adjudicated (judicially defined) form of private property with a very high level of protection for other water rights that might be affected by changes in place, kind, or time of use. That principle of "no injury" has been articulated by the requirement that parties seeking a change bear the burden of proof, and in practice that has meant high engineering and legal fees to get change decrees from water courts (Nichols et al. 2001, Corbridge and Rice 1999, Hobbs 1997 et seq.) . Further, there have been only very limited opportunities for leases or temporary transfers, or the kinds of sharing or conditional transfers that academics have recommended (and which are the subject of this presentation). Colorado's lead in formalizing the transfer process has helped to very clearly specify the property rights, which is important for markets. But this is also an inflexible system with high transactions costs (costs of making a deal), which discourages small-volume transfers and may also favor the small set of large-volume buyers relative to many more sellers, operating in a competitive private market. Inflexible water allocation is associated with economic inefficiency, and there have been many calls for improvements in water markets (Howe 2000, WWPRAC 1998).

The transfer of water from one use to another has been further complicated by the historic legacy of 19th century frontier misunderstandings of groundwater hydrology. Even now we are still adjusting to modern hydrologic modeling capacity and the ability to manage coherently. In Colorado, well-users are still not fully integrated into prior appropriation, as recent shut-downs in the South Platte have shown, while the Rio Grande Basin is developing management changes, and in California there have been odd disconnections such as allowing surface rights leases to the Water Bank and use of ground water, for example (McGuire 2006; Slater 2005, Strawn 2004, Hobbs 1997 et seq.). Transfers and substitutions are being rationalized, but the high engineering costs of modeling depletion of surface flows from well pumping, and specification of required augmentation of flows has slowed adjustment.

Can we do better? Desirable features would include less cost and delay (it takes literally years, usually) and less missed opportunity (Howe and Goemans 2003, Nichols et al. 2001). Better markets with adequate technical support and administrative capacity would enable rather than defeat efforts to achieve efficiency of use, while protecting other water rights. Better institutions would increase knowledge of water prices, and allow low-cost estimation of what is transferable. Ideal markets with good technical support would also provide greater knowledge of the resources available, and some foresight of the cumulative limits and thresholds of impact that can abruptly limit activity, such as need to respond to water quality or endangered species situations. Better markets would not include concealment of dealings and prices (see Olinger et al. 2005). Better markets would include participation by important recreational and environmental interests, by modernizing limits on allowed uses of water (Neuman

1998, Hobbs 1997). Better public information would increase ability for all interests to seek what they value in the market. Recreational and environmental interests increasingly appear in markets for land resources; 24 billion dollars in local conservation funding was approved by voters between 1998 and 2003 (Newburn et al., 2006). Recreation and environment are a very large part of the economy and are at risk from dependence on resources they cannot rely on (Environment Colorado 2006, Harmon 2005, Weller 2005, Governor's Commission 2000).

Re-allocation of agricultural water affects many public interests and public goods. Those benefits are shared by almost all, in some sense, but are provided by the actions of a few at their own expense, and so are likely to be under-provided. There is also public interest in avoiding uncertainties and high costs from sudden imposition of limits such as may be imposed by total maximum daily loads affecting water quality and Endangered Species Act limitations, as shown in major river basin programs on the Platte and Colorado Rivers (e.g. Bureau of Reclamation 2003). Environmental problems often arise from changing the place of use of water, which changes flow timing and patterns that may be critical for fisheries. Social and socio-economic issues include a large range of externalities, worst in particularly agriculture-dependent areas (Howe and Goemans 2003, Howe 2000). These include losses of economic activity and local tax bases, which affect many interests not involved in the sale of the water. Also, the problems we confront include synergistic interaction with impending climate change. No assessments are optimistic for irrigated agriculture in the Central Plains (Edmonds et al. 2005, Barnett et al. 2004) or mountain west. It is important that the practical implications for the rural economy are the same as for rural environmental stability (Environment Colorado 2006, Matthews 2006). For many reasons, we need quick progress in establishing management which can provide the adaptive capacity to respond to changing conditions and maintain resources, and that in turn requires the social process of institutional change (Wiener 2005). Finally, there has been too much investment in existing property rights to expect an easier answer than ways that respect those rights and the laws defending them.

MISSING FORMS OF WATER TRANSFER

The Colorado Statewide Water Supply Initiative has included technical roundtable review of different forms of water transfer, including different kinds of leases, and other alternatives to "buy-and-dry" (Colorado Water Conservation Board website). Three forms of transfer may serve to meet many of the needs noted above, provided that no additional barriers to participation arise.

1. Spot Market (Water Bank) For Short-term Transfers

There is substantial West-wide interest in improving short-term transfers (often kinds of leases) with very low costs and rapid implementation, for a wide variety of purposes (see survey in Clifford et al. 2004). In Colorado, short-terms of up to 2 years may be best, with administrative rather than judicial approval, but subject to review of presumptions of transferable historic consumptive use and other findings of fact. Where a spot market exists, it has served agricultural as well as municipal interests (Howe and Goemans 2003, Michelsen 1994). Flexibility is valuable for irrigators to react to surprises and opportunities which may occur, (e.g. expectations for markets due to local or competitor region conditions), and for security of investment in high-capital technology where infrequent needs arise to maintain investment (e.g. fruit trees, greenhouses). The persistence of an established water market is important, because it supports expectations even with variable prices (Slater 2005, Neuman 2004, Howe and Goemans 2003); other commodities are often traded this way (e.g. gasoline). "Thick" often-used markets provide price discovery and information. A working market like this exists only in the unique case of the Northern Colorado Water Conservancy District, because of the legal framework allowing almost instant cost-free transfer of water which has already been transferred to the District. No other Colorado district has this legal structure, and in the US it is almost unique, though some entities allow easy transfer within districts if the use stays in farming.

2. Rotational Crop Management For Long-term "Base-load" Transfers

The idea came to us from California examples in large Bureau of Reclamation client irrigation districts (Raby and Devine 2004, MacDonnell and Rice 1994). Crop rotation designed to accommodate predictable reductions of irrigation water on part of the area would "free up" transferable water while minimizing disruption of farming. The most innovative feature is a very long-term contract, lasting many decades, which would require extensive negotiation and probably effort to self-organize by transferors. The intended use is to provide "base-load" annual municipal supply (perhaps for high-value agriculture as well). This has been authorized (HB06-1124) by law signed May 25th, 2006, but not yet attempted.

Transferees would probably incur initial costs for infrastructural investments such as check-dams and canal improvements to enable flexible irrigation management. But, acquiring water this way avoids the need for cities to issue bonds and pay interest on money to buy the water right (e.g. at 3.25% interest, and 1-3% cost for establishing the bonding mechanism, a million dollars on a 30 year term costs almost $1.6 million). Billing through water rates and tap fees for "pay-as-you-go" matches costs and benefits far more accurately across the time and users. Municipalities limited in their bonding capacity may benefit from conserving debt capability, or avoiding creation of new entities.

Payments for increased system operation costs, with ditch companies and irrigation districts being parties, would probably accompany payments to participants, perhaps larger to those foregoing irrigation; the size and distribution of the pie are negotiable, and the parties can make their own deals. The asset value and appreciation would be retained by the transferors, subject to the servitude created by the contract, and subject to the deal agreed concerning the options at the end of the term as well as other contingencies. After many decades, it seems unlikely that users of a long-operating and installed contractual and physical system would suddenly face hot competition, but risk allocation is the essence of a contract and this can be anticipated. The most remarkable consequence is the prospect for long-term stability in the agricultural operations, perhaps for the first time. The people, land, and un-contracted water are as free as before the contract.

3. Interruptible Supply Agreements for Long-term Occasional Transfers

The interruptible supply idea for very long terms is quite similar to the rotating crop management idea, but the transfer would take place on specified contingencies (including requests for any reason if so agreed) which are not as temporally predictable. This form would serve three main purposes for transferees: (1) *dry-year and post-drought recovery* "calls" on a schedule of price adjustments to account for the time when the option is exercised and cover expenses; (2) *facility-out-of-service* substitutions, same schedule of price/time of call; and (3), *wet-year calls* at different set of prices to enable storage filling, aquifer storage or recharge, etc. while the farmer uses the wet year for not, less or differently irrigated crops, probably on a different schedule of payments. All would involve negotiated risk sharing arrangements. Transferees would use these to firm supply, and in some cases, operate existing infrastructure with minimal additional investment (e.g. to fill storage not being filled by normal sources). Transferors would receive income just when farming is least likely to provide good yields, though prices for feed are most likely to be high and crops would be lucrative for those able to produce. As coordination and planning increase, one would expect to see *increasingly meshed sets of contracts* and agreements. Discussions indicate that farmers would prefer to have all options open, as one would expect, and to be able to use spot markets, for example, to support investments while engaging in long-term deals.

SUGGESTED PRINCIPLES FOR WATER TRANSFERS

Role of the State. The state should be the "referee" for technical and administrative management, to protect water and other property rights, defend interests in water quality, soil erosion etc., and manage social impacts as directed. It should provide adequate information and institutions to allow successful markets and reduce transactions costs. It should assure certainty of priority. And, it should foster capacity of local governments to identify and secure needs and interests.

Role of the Market. Markets should provide fair and reasonably transparent opportunity for trades of resources and arrangements for risk distribution and management, including opportunity for third-parties and governments to seek or preserve conditions they desire, for amenity, tax-related, recreational, environmental or other interests, by purchase, lease, easement or otherwise. Market allocation is preferred to political processes because it allows negotiation flexibility for unique needs and desires, and certainty of property rights.

Certainty. Establishing alternatives to the sale of water rights requires low-cost specification of property interests and also adequate efforts to foresee and manage impacts and surprises. Failure to anticipate thresholds and limits will threaten certainty, so scales and quality of assessment must be sufficient to anticipate adverse surprises. Parties who are surprisingly excluded may threaten the legitimacy and certainty of arrangements privately made which suddenly prevent others' participation.

Allocation within Thresholds. Failure to anticipate thresholds has been very injurious, as recently illustrated in the South Platte where well users were abruptly brought into compliance with prior appropriation or shut down (McGuire 2006). However a threshold arises, from physical limits, water law, or policy, there will be need to allocate and reallocate within the limit as situations change.

Transferor "Internal" Allocation by Market. Two sets of internal adjustments should be possible within transferor organizations. First, resource re-allocation for purposes sought by outsiders, such as salinity reduction or environmental conservation may be important. Second, individual situations may call for flexibility within transferor organizations such as groups of mutual ditch companies. Farmers and their families may want different outcomes and things change. Certainty in the long term requires internal adjustability on the small scale, and adequate scale to accommodate individual property rights and preferences.

Scale Matters, and Appropriate Collaborative Institutions. Impacts are related to scale and cumulative impacts are often regional. Identification of impacts and interests is somewhat new in relation to water transfers, partly because of the history of externality and mitigation issues without remedy and lack of public interest consideration in water transfer cases (Slater 2005, Howe 2000, MacDonnell et al. 1994). Adequate organizations (existing ditch companies or districts, or collaborative sets, perhaps) are needed to manage impact assessment and to adapt as needed. There may also be value in regional recreational and environmental considerations, to introduce interests new to the market and identify opportunities for coordination and efficiency. Wider participation in markets should more fairly match and help internalize costs and benefits. Scale issues include the areal extent of transferor organizations, regional impacts and participant preferences, as well as costs of management and organization.

LOOKING FOR TROUBLE: WHAT IF WE GET THESE OPTIONS?

Although the alternative forms of transfer are not "new" (e.g. Michelsen and Young 1993, MacDonnell and Rice 1994), research to explicitly support them had not appeared to an expert panel convened in February 2006, in association with the Central Plains Irrigation Association meeting, or in years of inquiry and participation in water discussions. The following notes partly reflect that panel discussion. It was agreed that risks of a failed innovation may include discrediting the innovation instead of the attempt. No qualitatively different problems for these forms have yet been identified, compared to "buy-and-dry", except the need for innovative contracting negotiation and the retreat from an initial demand for "permanence" in water acquisitions for municipalities. This has been especially prominent where the officials perform professional roles oriented solely to acquisition and management of water supply rather than serving constituencies whose interests are complex.

On-farm issues partly overlap with the many problems created by "buy-and-dry", but since the new forms avoid permanent dry-up they reduce them a great deal, particularly soil and fertilizer management issues. Tillage and equipment usage would very likely be shifted, with no-till and anti-erosion measures emphasized as well as moisture retention practices. Capital equipment and financing problems are simplified with very long planning horizons, made possible by the very long term contracts contemplated, and it becomes possible to consider management for maximum economic yield rather than maximum possible harvests. The ideal rotations for either rotating crop management or safe use of interruptible supply agreements will likely involve reduced sizes of harvest, but profitability reflects expenses as well as gross revenues, and net for the operation will reflect payments for the water transferred and other contract terms. Compatibility with other activity (agritourism, wildlife access, and assorted USDA programs, etc.) may add value. Adjustments may take some time, though that would be available, for a change! Farm families would have more choice.

Off-farm social and economic issues appear to be considerably more manageable in comparison to the "buy-and-dry" approach. At least during adjustment periods, some reduction in activity and labor will likely induce secondary impacts to both forward and backward linkages to the farming enterprise, and pecuniary impacts to local economies, but these would be much less than where large volumes of water are sold, even if they are leased back for some period. Retaining an ownership interest supports intensification and improvement of agricultural activity; this may be especially important in marginal commodity production as well as near-urban areas where agriculture's open space supports other values (Environment Colorado 2006, Hellerstein et al. 2002, Governor's Commission 2000). Preservation of ditches and irrigation districts as functional units may have social as well as environmental benefit.

Unforeseeable biological problems may result from de-watering agricultural land and canals which have become a partial substitute for riverine and wetlands environments converted to agricultural use. River mainstems have already undergone profound changes in fluvial processes and flow hydrographs, and geomorphology, resulting in biological community change and successional novelties little examined since they occur on private lands offering limited access. Additional concerns relate to soil degradation and loss of fertility due to discontinuation of irrigation after very long periods, and off-farm concerns for erosion and run-off. Mainstem ecological changes are widely observed, in problems of invasive species, but there is little investigation of cumulative impacts on private land and water. The irrigated areas are now "hybrid ecologies" (Crifasi 2005) highly dependent on human water management providing the partial substitute for riparian, wetland, and other environmentally important areas. Almost no water is unchanged somehow. But reform in allocation which did not include currently non-market interests and values, as discussed above, could mean hitting more thresholds faster.

The three most threatening problems may be (1) the lack of social organization needed for the irrigators to engage constructively with the opportunities as well as to defend their interests, (2) the myopic urban preference for permanent water sales regardless of long-term interests, and (3) the underinvestment in resource assessment that threatens public interests in environment, recreation, and amenity. All of these are curable, but delay is expensive.

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REFERENCES

Barnett, T., R. Malone, W. Pennell, D. Stammer, B. Semtner and W. Washington, 2004, The effects of climate change on water resources in the West: introduction and overview. [Introduction to special issue.] *Climatic Change* 62 (1): 1-11.

Bureau of Reclamation, and U.S. Fish and Wildlife Service, Department of the Interior, 2003, *Platte River Recovery Implementation Program Draft Environmental Impact Statement.* Denver: Bureau of Reclamation

Clifford, P., C. Landry, and A. Larsen-Hayden, 2004, *Analysis of Water Banks in the Western States*. Washington State Department of Ecology, and WestWater Research; available from <http://www.ecy.wa.gov/biblio/0411011>.

Colorado Water Conservation Board, 2004, 2005, 2006: Statewide Water Supply Initiative. Various reports available at: <www.cwcb.state.co.us/swsi/>

Corbridge, J. and T. Rice, 1999, *Vranesh's Colorado Water Law*, Rev. Ed., Niwot, CO: University Press of Colorado.

Crifasi, R.R., 2005, Reflections in a Stock Pond: Are Anthropogenically Derived Freshwater Ecosystems Natural, Artificial, or Something Else? *Environmental Management* 36(5): 625-639.

Edmonds, J.A. and N.J. Rosenberg, 2005, Climate change impacts for the conterminous USA: An integrated assessment summary [summary of special issue). *Climatic Change* 69(1): 151-162.

Environment Colorado, 2006, *Losing Ground: Colorado's Vanishing Agricultural Landscape*. Denver, CO. <www.environmentcolorado.org>.

Governor's Commission on Saving Farms, Ranches and Open Space, 2000, *Natural Landscapes: Colorado's Legacy to its Children*. Available from website of the Office of the Governor, State of Colorado.

Harmon, T., 2005, "A river of cash: rafting way up; revenues rise 17%", *Pueblo Chieftain*, 10 December 2005.

Hellerstein et al., 2002, *Farmland Protection: the Role of Public Preferences for Rural America.* Washington: USDA, ERS Agricultural Economics Report No. 815, available on-line.

Hobbs, G.J., Jr., 1997, Colorado Water Law: An Historical Overview. 1 *U. Denver Water L. Rev*. 1; updates 2 *U. Denver Water L. Rev*. 223, (1999), 4 *U . Denver Water L. Rev*. 111, (2000), 6 *U. Denver Water L. Rev*. 116, (2002), 8 *U. Denver Water L. Rev*. 213 (2004).

Howe, C.W., 2000, Protecting Public Values in a Water Market Setting: Improving Water markets to Increase Economic Efficiency and Equity. *University of Denver Water Law Review* 3(2): 357-372

Howe, C.W. and C. Goemans, 2003, Water Transfers and their Impacts: Lessons from Three Colorado Water Markets. *Journal of the American Water Resources Association* 39(5): 1055-1065.

MacDonnell, L.J. and T.A. Rice, 1994, Moving Agricultural Water to Cities: The search for smarter approaches. *Hastings North-Northwest J. Environmental Law and Policy* 2: 27-55.

McGuire, K., 2006, Owens goes to well for farmers – U.S. aid available to those suffering loss from water shut-off. *Denver Post* 11 May 2006.

Michelsen, A.M., 1994, Administrative, Institutional and Structural Characteristics of an Active Water Market. *Water Resources Bulletin* 30(6): 971-982.

Michelsen, A.M. and R. A. Young, 1993, Optioning Agricultural Water Rights for Urban Water Supplies During Drought. *American Journal of Agricultural Economics* 75(4): 1010-1020.

National Research Council, 2004, Confronting the Nation's Water Problems: The Role of Research, Washington, D.C.: National Academy Press.

Neuman, J. C., 1998, Beneficial Use, Waste and Forfeiture: the Inefficient Search for Efficiency in Western Water Use. 28 *Environmental Law* 919.

Newburn, D.A., P. Berck and A.M. Merenlender, 2006, Habitat and Open Space at Risk of Land-Use Conversion: Targeting Strategies for Land Conservation. *American Journal of Agricultural Economics* 88(1): 28-42.

Nichols, P.D., M.K. Murphy, and D.S. Kenney, 2001, *Water and Growth in Colorado: A review of Legal and Policy Issues*. Boulder: University of Colorado, Natural Resources Law Center.

Olinger, D. and C. Plunkett et al., 2005, "Liquid Assets – Turning Water into Gold", multi-part series with sidebars, 21, 22, and 23 November 2005, The Denver Post.

Raby, N. and A.J. Devine, 2004, The Imperial Valley-San Diego Water Transfer Agreement: A Case Study of Property Rights in Collective Action. Pp 83-93 in US Committee on Irrigation and Drainage, *Proceedings, 2004: Water Rights and Related Water Supply Issues*. Denver, CO: USCID.

Slater, S.S., 2005, A Prescription for Fulfilling the Promise of a Robust Water Market. 36 *McGeorge L. Rev.* 253.

Strawn, L., 2004, The Last Gasp: The Conflict Over Management of Replacement Water in the South Platte River Basin. *U. of Colorado L. Rev.* 75: 597-632.

Weller, R., 2005, "A mountain of money: Vail Resorts proud of record $81 lift ticket", Associated Press, *The Pueblo Chieftain*, published 10 December 2005

Western Water Policy Review Advisory Commission, 1998, *Water in the West*. Available from National Technical Information Service, Port Royal, Virginia.

Wiener, J.D., 2005, presentation at Climate Prediction Applications Science Workshop, International Research Institute for Climate Prediction, at http://iri.columbia.edu/outreach/meeting/CPASW2005/Presentation/JWiener.pdf

AGRIMET: A TOOL FOR IRRIGATION WATER MANAGEMENT

Peter L. Palmer[1]

ABSTRACT

Competition for limited water resources in the western United States continues to increase. In most western states, irrigated agriculture is the largest single consumer of water. To help improve irrigation efficiency, the Bureau of Reclamation and Bonneville Power Administration partnered to create a network of automated agricultural weather stations - called "AgriMet" - in the Pacific Northwest. These stations collect and telemeter the meteorological parameters required to model crop evapotranspiration (ET). The information is used by irrigation districts, farmers, resource conservation agencies, and agricultural consultants for irrigation scheduling and related purposes. Since the initial installation of 3 stations in 1983, the network has grown to over 60 stations in Reclamation's Pacific Northwest region, 21 stations in the Great Plains Region in Montana, and seven stations in the Mid Pacific region. These automated weather stations transmit their data by the GOES satellite, and the information is used in the Kimberly-Penman 1982 evapotranspiration model to compute reference ET at each station. Crop coefficients are then applied to estimate water use for specific crops grown at each station for every day of the growing season. This information is available on the Internet, and is integrated into various on-farm technical assistance programs by local agricultural consultants, the Cooperative Extension Service, and the USDA Natural Resources Conservation Service. Use of AgriMet information in irrigation scheduling results in water and energy savings, reduced soil erosion, and protection of surface and ground water supplies. Various agricultural consultants have reported water and power savings ranging from 15 to 50 percent (Dockter, 1996). Some irrigators have reported real savings of as much as $25 per acre in pumping costs after using AgriMet ET data to schedule their irrigations (Palmer, 2004).

INTRODUCTION

Modeling evapotranspiration (ET) with weather data has evolved over the years with refinements in modeling procedures and data collection methods. Current technologies typically involve automated agricultural weather stations and data transfer by satellite, phone, radio, or wireless networking. Powerful computers

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[1] AgriMet Program Coordinator, U.S. Bureau of Reclamation, Pacific Northwest Region, 1150 N. Curtis Road, Suite 100 Boise, Idaho 83706-1234, (208) 378-5283. ppalmer@pn.usbr.gov

now make fast work of the typically complex mathematical ET models, and the Internet makes the information almost instantly available to the users.

The U.S. Bureau of Reclamation partnered with Bonneville Power Administration in 1983 in an effort to promote efficient irrigation water use. This partnership resulted in the installation of a network of automated agricultural weather stations called "AgriMet" (for Agricultural Meteorology) in the Pacific Northwest. These stations collect and telemeter the meteorological parameters required to model crop evapotranspiration (ET). Since the initial installation of 3 stations in 1983, the network has grown to over 60 stations in Reclamation's Pacific Northwest region, 21 stations in the Great Plains Region in Montana (east of the Continental Divide), and seven stations in the Mid Pacific region. Reclamation has established partnerships with more than 25 entities, including other federal and state agencies, soil and water conservation districts, universities, public utilities, and private businesses to help fund the operation of the AgriMet network. The Northwest Energy Efficiency Alliance, a consortium of electric utilities in the Northwest, provides significant financial support for the AgriMet network.

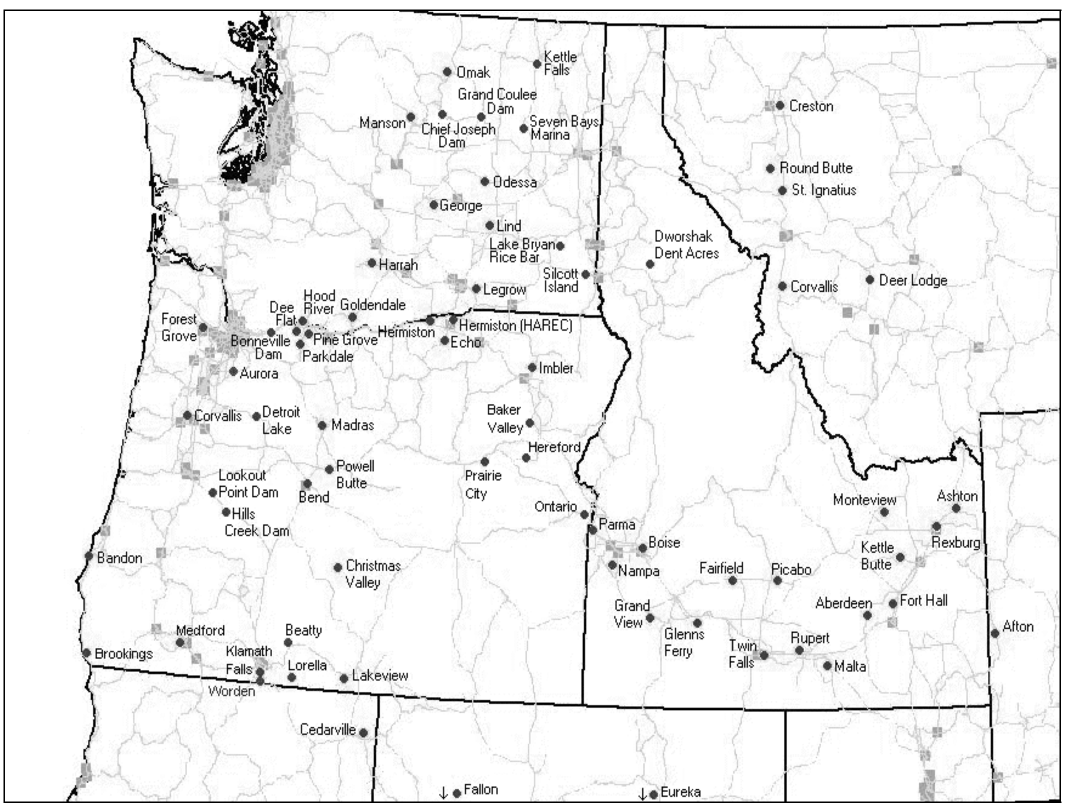

Figure 1. AgriMet Weather Station Locations in the Pacific Northwest Region

AGRIMET DATA COLLECTION AND TRANSMISSION

AgriMet stations are located in agricultural areas throughout Idaho, Montana, Oregon, and Washington, with additional stations located in northern California, western Wyoming, and Nevada. The stations are typically located on the edge of irrigated fields so that the observed weather data approximates the meteorological conditions affecting the cultivated crops in the area (Fig. 2). Each AgriMet station is configured with a standard set of sensors, including air temperature, precipitation, solar radiation, wind speed and direction, and relative humidity. These standard sensors measure the meteorological parameters required for modeling crop ET. Some sites have special sensors, including soil temperature, diffuse pyranometers for special solar radiation studies, crop canopy temperature, leaf wetness, and evaporation pan sensors.

All the weather station components, including sensors, solar panel, antenna, data logger and transmitter are mounted on a sturdy aluminum tripod. Sensors are mounted at standard sensor heights for agricultural weather data collection requirements. Power for each weather station is provided by a heavy duty lead acid storage battery that is recharged daily by a solar panel.

The data logger at the site monitors each of the sensors once every second. These readings are used to derive the final data parameters for subsequent transmission, such as 15 minute air temperature observations, total hourly precipitation, etc. These parameters are transmitted from the weather stations via the GOES satellite

Figure 2. Typical AgriMet Weather Station

(Geostationary Operational Environmental Satellite) to a receive site at the Bureau of Reclamation's Pacific Northwest Regional Office in Boise, Idaho. The receive site also down-links data for other Reclamation programs, as well as for other cooperating federal agencies. An effort is currently underway to upgrade all AgriMet stations from one transmission every four hours to hourly transmissions, improving the timeliness and hence the usefulness of the weather data. As of 2006, well over half the AgriMet stations have been upgraded to transmit on an hourly basis.

All AgriMet sites receive an annual maintenance and inspection visit in the spring that includes calibration and maintenance of all sensors. Data logger and transmitter parameters are checked for conformance to specifications. System battery voltage, solar panel output, and voltage regulator output are checked; these items are replaced or adjusted as needed. All sensors are compared against laboratory calibrated standards and are adjusted or replaced as needed. This special attention given to the sites during these annual calibration and maintenance visits provides high quality meteorological data not only for crop water use modeling, but also for a variety of research and other weather related applications.

Data Quality Control Procedures

Upon receipt of the weather data from the GOES satellite, it is subjected to a variety of automated quality control procedures. These validation tests include a check of satellite transmission data quality parameters, upper and lower value limit tests, and rate of change tests. If the incoming data fails any of these checks, it is marked with a flag indicating the nature of the failure before being added to the database. These flagged values are not used in subsequent calculations, such as computation of average daily temperatures or daily ET rates. After these automated quality control processes are completed, the 15 minute (and hourly) data are stored in a "dayfiles" database. Standard AgriMet dayfile parameters include instantaneous air temperature and relative humidity, computed dew point, peak wind gust, average wind speed and wind direction -- all on 15 minute intervals. Hourly data includes accumulated wind run, accumulated solar radiation, and accumulated precipitation.

Between 5:00 and 5:30 am each morning, several automated processes run on the dayfiles data, producing summary parameters for the previous day, including daily maximum, minimum, and average air temperatures, total daily wind run, average wind direction, peak wind gust, total daily precipitation, total daily solar radiation, mean relative humidity, mean dew point, and reference ET. These data are stored in an "archive" database. All of the historical weather information (both hourly/15 minute and daily summaries) are available on the AgriMet website for the period of record.

In addition to the automated checks, a manual quality control review is performed on the data each working day. These procedures include review of satellite transmission quality parameters that may point to data quality problems not detected by the automated procedures. Other checks include graphical review of sensor data by groups of sites that have similar climatic characteristics. Apparent anomalies are examined for possible data quality problems, and bad data are removed or estimated. Archive parameters and ET values are then recalculated using the revised data parameters. These changes are then reposted to the AgriMet website. AgriMet's quality control procedures result in a very complete, accurate, and timely database of meteorologic information, easily available on the Internet.

EVAPOTRANSPIRATION MODELING

AgriMet uses the 1982 Kimberly-Penman equation for computing reference ET, adapted by Dr. James L. Wright of the USDA Agricultural Research Service through his research performed in Kimberly, Idaho (Jensen et al., 1990). This procedure requires several meteorological inputs for modeling ET, including maximum and minimum daily air temperatures, relative humidity, daily solar radiation, and daily wind run. All of these parameters are collected by the AgriMet system.

The 1982 Kimberly-Penman uses alfalfa as the reference crop with reference conditions defined as a well-watered alfalfa crop with 30 to 50 cm of top growth. The equation, as implemented in the AgriMet program, is represented as:

$$\lambda ET_r = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} 6.43\, W_f (e_s - e_a) \qquad (1)$$

Where:

λET_r is reference evapotranspiration
Δ is the slope of the saturation vapor pressure-temperature curve
γ is the psychrometric constant
R_n is the net radiation
G is the soil heat flux
6.43 is the constant of proportionality in $MJ/m^2/d/kPa$.
W_f is the dimensionless wind function
$(e_s - e_a)$ is the mean daily vapor pressure deficit in kPa.

Because of the variability of ET rates from crop to crop and the complexity of modeling ET, the accepted standard for deriving crop specific ET (ETc) is to model ET for a reference crop, such as alfalfa (ETr), and then apply this reference ETr value to specific crops through the use of crop coefficients (Kc). These crop coefficients are unique to the reference crop and the individual specific crop, and they vary through time with the growth stage of the plant. These crop coefficients typically are expressed as percent of water use compared to the reference crop (see figure 3). In equation form, the crop coefficient methodology is represented as:

$$ETc = ETr * Kc \tag{2}$$

Where:

ETc = Crop specific evapotranspiration
ETr = Reference evapotranspiration (alfalfa reference)
Kc = Crop coefficient for a specific crop.

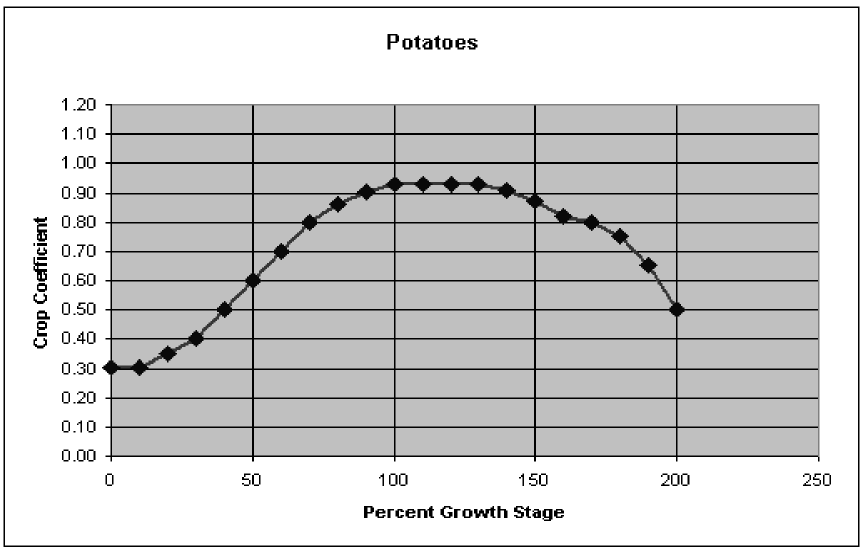

Figure 3. Example of Crop Coefficient Curve used by AgriMet

These crop coefficients have been developed by a variety of researchers and research methods (Jensen, et al., 1990). Most of the crop coefficients used by AgriMet, however, were developed using weighing lysimeters at the USDA ARS Research Center in Kimberly, Idaho. Application of these crop coefficients requires, at a minimum, knowledge of the emergence date (or green up date, in the case of perennial plants) for each crop in the vicinity of each weather station. Local contacts (such as county extension agents, crop consultants, or producers) provide this input each spring in order to calibrate the AgriMet crop models to local conditions for that year. The result is a table of daily ET for each crop grown in the vicinity of each AgriMet station (Table 1).

Table 1. Daily AgriMet Crop Water Use Chart

ESTIMATED CROP WATER USE - JUL 6, 1998 Ashton, Idaho

CROP	START DATE	DAILY CROP WATER USE-(IN) PENMAN ET - JUL 2	3	4	5	DAILY FORE CAST	COVER DATE	TERM DATE	SUM ET	7 DAY USE	14 DAY USE
ALFALFA	501	0.35	0.32	0.29	0.23	0.28	625	925	9.3	2.0	3.3
PASTURE	420	0.24	0.22	0.20	0.16	0.19	610	925	8.1	1.4	2.3
LAWN	420	0.28	0.26	0.23	0.18	0.22	601	925	9.9	1.6	2.7
W GRAIN	415	0.35	0.32	0.29	0.23	0.28	625	815	12.1	2.0	3.3
S GRAIN	520	0.34	0.31	0.29	0.23	0.28	801	901	5.6	2.0	3.2
POTATO	620	0.12	0.12	0.11	0.09	0.11	815	1015	1.2	0.7	1.1

There are four major products provided by the AgriMet program:

- A table of daily ET values for the last five days for a reference crop (Alfalfa) and specific crops grown in the area. This table includes a 7-day, 14-day, and growing season ET total. In addition, a forecast of ET for the current day is displayed (based on the average of the last three days ET value) (see Table 1).
- A table of weather parameters for the last 5 days or 10 days for each station.
- A summary of ET for each day of the growing season for each crop grown in the vicinity of each station.
- Historical weather and crop water use data for all stations for the entire period of record.

All of these products are available from Reclamation's AgriMet website at http://www.usbr.gov/pn/agrimet. Information for the Great Plains AgriMet program (east of the continental divide in Montana) is available at http://www.usbr.gov/gp/agrimet/index.cfm. Several local newspapers in the region publish AgriMet crop water use during the growing season, providing an additional means of local dissemination. AgriMet information is further distributed to the user by county extension agents, producer cooperatives, and crop consultants.

USES OF AGRIMET PRODUCTS AND INFORMATION

AgriMet crop water use information is integrated into various on-farm technical assistance programs by local agricultural consultants, the Cooperative Extension Service, and the USDA Natural Resources Conservation Service. As competition for limited water supplies increases - as well as the cost of pumping for irrigation - farmers are turning more and more to scientific irrigation scheduling.

The most common method for irrigation scheduling is known as the "checkbook method," accounting for deposits and withdrawals to the soil moisture balance. For this procedure, the farmer must first know the plant root depth and water holding capacity of his soil. This information is typically available from detailed soil surveys of the area, or from site specific soil tests. After each irrigation during the growing season, the farmer tracks the daily crop specific ET, available from AgriMet. When the cumulative water use equals the Management Allowable Depletion (MAD) for that crop, it's time to irrigate again. Specific knowledge of the irrigation system, combined with ET information from AgriMet, allows a farmer to apply the right amount of water at the right time for optimum crop production. Not only does the farmer realize savings in water and pumping costs, but reduced leaching results in reduced costs for fertilizer, herbicides, and pesticides. Various agricultural consultants have reported water and power savings ranging from 15 to 50 percent through the use of AgriMet supplied ET data (Dockter, 1996). Some irrigators have reported real savings of as much as $25 per acre in pumping costs after using AgriMet ET data to schedule their irrigations (Palmer, 2004). Indirect benefits of scientific irrigation scheduling include reduction in non-point source surface water pollution (through reductions in nutrient and chemical laden irrigation tail water) as well as protecting ground water supplies through reduced leaching of agricultural chemicals.

AgriMet ET information is being extensively used by irrigators for on-farm irrigation water management. In a study conducted for the Bonneville Power Administration, "on-line services, primarily AgriMet, are the most commonly used source for obtaining this (ET) information and account for 45 percent of cases. These figures, however, under-represent the actual use of ET information, particularly from AgriMet, since they do not take into account cases where commercial irrigation service providers provide this data" (Kema-Xenergy, Inc., 2003).

Through scientific irrigation scheduling, AgriMet offers significant opportunities for farmers and irrigators to reduce their use of limited irrigation water supplies. There are financial incentives to do so, beyond just the costs of water and the power required to move it. For example, in a case study conducted by Oregon State University (English, 2002), an economic analysis was conducted on a 125 acre center pivot of potatoes in Washington supplied by a pump with 700 feet of total lift . Assuming 19% excess water use (a typical value, according to the study), and a low sensitivity to the excess water (resulting in a 3% yield loss), the extra costs to the farmer included:

Energy Cost:	$ 1,490
Nitrogen Leaching:	$ 5,625
Yield Reduction:	$ 10,890
Total Cost:	$ 18,005

In the Lake Chelan area of Washington, the local irrigation district uses AgriMet data for site-specific irrigation scheduling (Cross, 1997). Manual soil moisture measurements are taken weekly at 2-4 sites per orchard in over 60 fruit orchards in the area. Daily AgriMet data is used to monitor the crop water use between field measurements. The soil moisture is plotted on a time series graph, showing soil moisture content at several depths through the growing season. When the AgriMet ET data indicates that the soil moisture has dropped to the management allowable depletion level, the producer irrigates the orchard. The next field measurement shows the new soil moisture levels, and the daily consumptive use values from AgriMet are systematically subtracted from the soil moisture levels until the next irrigation is scheduled. This process is repeated throughout the growing season, and updated information is provided to each producer on the same day the soil moisture measurements are taken.

AgriMet weather data are used for a variety of applications in addition to ET computation, and requests for current and historical weather information from the AgriMet network are common. Agricultural producers depend on wind speed and direction for scheduling such practices as field burning and pesticide applications. Weather data is used by state DEQ's for investigating pesticide application and ground water contamination issues. The National Weather Service uses AgriMet weather data for short term forecasting and forecast verification. Several electric utilities use the weather information to forecast daily energy requirements, including peaking power. University researchers frequently use AgriMet data for a variety of applications, ranging from regional consumptive water use modeling to locating new orchards. ET information is being used by other agencies, such as the National Resources Conservation Service, to document compliance with irrigation water management practices on individual farm tracts. Increasingly, ET information from weather station networks is being used in water rights management by state water resource agencies.

SUMMARY

In the early 1980's, the U.S. Bureau of Reclamation, in partnership with Bonneville Power Administration, developed a network of automated agricultural weather stations in the Pacific Northwest. From the original three sites installed in 1983, the AgriMet system has now grown to over 90 sites in Idaho, Oregon, Washington, Montana, Wyoming, and California. Reclamation has cultivated partnerships with over 25 federal, state, and private interests to help fund the operation of the network.

AgriMet stations collect the weather data required for modeling crop evapotranspiration and transmits this information via satellite to Reclamation's Regional Office in Boise, Idaho. Every day during the growing season, crop water use charts are developed for crops grown in the vicinity of each AgriMet

station. This information is available daily through the Internet and is also published in many local newspapers throughout the region. The information is used by federal and state agencies, conservation districts, irrigation districts, extension agents, agricultural consultants, corporate farms, and individual irrigators for water management purposes. The weather data collected is also used for a wide variety of other applications. A rigorous field calibration and maintenance program, and data quality assurance program ensures a high level of data quality and integrity.

Competition for limited water resources is increasing, cost of irrigation water and pumping is rising, and concerns for surface and ground water quality are heightening. In response to these factors, scientific irrigation scheduling is becoming more commonplace. AgriMet is providing the information required to meet these challenges in the Pacific Northwest.

REFERENCES

Cross, Paul., 1997. Lake Chelan Reclamation District, Personal Communication, October, 1997.

Dockter, Douglas T., 1996. "AgriMet - Applied Technology for Agricultural Conservation". Proceedings of Conserv96, January 4-8, 1996, Orlando, Florida, pp. 41-45. Proceedings published by American Water Works Association, Denver, Colorado.

English, Marshall, 2002. PowerPoint Presentation on Irrigation Scheduling. Oregon State University.

Jensen, M.E., Burman, R.D., and Allen, R.G., editors, 1990. "Evapotranspiration and Irrigation Water Requirements." Committee on Irrigation Water Requirements of the Irrigation and Drainage Division of the American Society of Civil Engineers, New York, N.Y.

Kema-Xenergy, Inc., 2003. "A Study of Irrigation Scheduling Practices in the Northwest". Prepared for Bonneville Power Administration, Portland, Oregon, September 5, 2003. Principal Investigators: Hossein Haeri, Kema-Xenergy and Marshall English, Oregon State University

Palmer, Peter L., 2004. Personal communication with Jeff Harper, an irrigator in Mountain Home, Idaho, who farms 1400 irrigated acres. April 19, 2004.

APPLICATION OF MODIS AND LANDSAT BASED EVAPOTRANSPIRATION FOR WESTERN STATES WATER MANAGEMENT

Masahiro Tasumi[1]
Richard G. Allen[2]
Ricardo Trezza[3]
Anthony Morse[4]
William Kramber[5]

ABSTRACT

The METRIC evapotranspiration (ET) estimation model was applied using MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images in New Mexico to evaluate the applicability of MODIS images to ET estimation and water resources management. With the coarse resolution of MODIS (approximately 1km thermal resolution), MODIS was not found to be suitable for field-scale applications. In project and regional scale applications, MODIS has potential to contribute to ET estimation and water resources management. MODIS based ET maps for New Mexico were compared with Landsat based results for 12 dates. Average ET calculations using MODIS and Landsat applications were similar, indicating that MODIS images can be useful as an ET estimation tool in project and regional scale applications.

INTRODUCTION

Quantifying the consumption of water over large areas and within irrigated projects is important for water rights management, water resources planning and water regulation. Traditionally, ET from agricultural fields has been estimated by multiplying the weather-based reference ET by crop coefficients (K_c) determined according to the crop type and the crop growth stage (Doorenbos and Pruitt, 1977; Wright, 1981; Allen et al., 1998; ASCE-EWRI, 2005). However, there are typically some questions regarding whether the crops grown compare

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[1]Associate Professor, University of Miyazaki, 1-1, Gakuen Kibanadai-Nishi, Miyazaki-shi, Miyazaki 889-2192, JAPAN; tasumi@kimberly.uidaho.edu.
[2]Professor, University of Idaho, 3793N, 3600E, Kimberly ID 83341; rallen@kimberly.uidaho.edu.
[3]Visiting Associate Professor, University of Idaho, 3793N, 3600E, Kimberly ID 83341; rtrezza@kimberly.uidaho.edu.
[4]Geospatial Technology Section Manager, Idaho Department of Water Resources (IDWR), P.O.Box 83720, Boise, ID 83720-0098; tony.morse@idwr.idaho.gov.
[5]Senior Remote-Sensing Analyst, Idaho Department of Water Resources (IDWR), P.O.Box 83720, Boise, ID 83720-0098; bill.kramber@idwr.idaho.gov.

with the conditions represented by the K_c values, especially in water short areas. In addition, it is difficult to estimate the correct crop growth stage dates for large populations of crops and fields. Recent developments in satellite remote sensing ET models have enabled accurate estimates of ET and K_c for large populations of fields and water users and quantification of ground-water pumpage in areas where water extraction from underground is not measured.

METRIC (Mapping Evapotranspiration at high Resolution and with Internalized Calibration; Allen et al., 2007a) is an image processing model comprised of multiple submodels for calculating ET as a residual of the surface energy balance. METRIC is a variant of SEBAL, an energy balance process developed by Bastiaanssen and his associates (1995, 1998a,b, 2000, 2005). METRIC was extended for application to mountainous terrain and to provide tighter integration with ground-based reference ET. METRIC has been applied with Landsat images in southern Idaho, southern California and New Mexico to estimate monthly and seasonal ET for water rights accounting and for operation of ground water models (Allen et al., 2007b). ET “maps” (i.e., images) via METRIC provide the means to quantify the temporal and spatial distribution of ET on a field by field basis.

Thermal information is essential for surface energy balance models. However, the future of satellite-based, field-scale thermal measurements is not bright. The Landsat program may terminate thermal measurement in the future. The ASTER satellite system has limited image availability. Under these circumstances, MODIS may be the default system to use with ET mapping in the near future, even though the pixel resolution is much larger than for Landsat or ASTER. This paper describes an application of MODIS and Landsat images with METRIC ET mapping model in New Mexico.

METRIC MODEL

In METRIC, ET is determined from satellite imagery by applying an energy balance at the surface, where energy consumed by the ET process is calculated as a residual of the surface energy balance equation:

$$LE = R_n - G - H \tag{1}$$

where LE is the latent energy consumed by ET, R_n is net radiation, G is sensible heat flux conducted into the ground, and H is sensible heat flux to the air.

R_n is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes, including solar and thermal radiation:

$$R_n = R_{S\downarrow} - \alpha R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1-\tau_o)R_{L\downarrow} \tag{2}$$

where $R_{S\downarrow}$ is incoming shortwave radiation, α is surface albedo, $R_{L\downarrow}$ is incoming longwave radiation, $R_{L\uparrow}$ is outgoing longwave radiation, and τ_o is broad-band surface thermal emissivity.

Incoming shortwave radiation is calculated by analyzing the solar position and intensity of radiation (Allen et al., 2006). Surface albedo is calculated by integrating reflectivities from bands 1 – 5 and 7 of Landsat, or bands 1 – 7 of MODIS, and applying an operational atmospheric correction (Tasumi et al., 2007). Incoming longwave radiation is estimated using regionally calibrated equations, and outgoing longwave radiation is calculated by surface temperature (T_S) and emissivity.

In METRIC, soil heat flux is estimated as a function of R_n, T_S and a vegetation index. Sensible heat flux is estimated by analyzing the air-temperature gradient (dT) and aerodynamic resistance between two near surface heights (0.1 and 2 m above zero plane displacement), assuming dT varies linearly with radiometric T_S, and by taking two extreme “calibration pixels” from very dry and very wet agricultural surfaces (Allen et al., 2007a).

METRIC model has been tested with lysimeters (Tasumi et al., 2005) and applied in the western United States (Morse et al., 2000, 2001; Allen et al., 2005, 2007b). The calculated ET maps have been used for a number of purposes including water rights management, ground water pumpage monitoring, irrigation performance computation, developing regional crop coefficients, input to regional ground water models and for water rights transfer.

LANDSAT AND MODIS IMAGES

Landsat has been one of the primary operational earth observation satellites over the past three decades. With long-term historical image records and high spatial resolution of 30 m in the short wave bands and 60 to 120 m in the thermal band, Landsat images have been widely used for both research and non-research purposes. Landsat images provide ideal data for estimating ET from field scale to project/regional scale applications in arid and semi-arid regions.

MODIS, on board the Terra and Aqua satellites, has provided satellite images since 1998. Because MODIS produces highly automated, low cost images having more frequent coverage than Landsat, MODIS images have become widely used for earth observation at the moderate spatial resolution of 250 to 1000 meters. MODIS has several official “higher-level” image products, such as surface temperature, Leaf Area Index (LAI), and albedo (King et al., 2004; Wan, Z. 1999; Knyazikhin et al., 1999; Vermote and Vermeulen, 1999). These higher-level products are useful in some applications.

While some advantages are available, MODIS's two major disadvantages in ET mapping are the low spatial resolution and the difficulty of image quality controls. MODIS image resolution is 250m in the green and NIR bands, 500m for the five other visible and NIR bands, and 1000m for thermal. However, these resolutions are when the satellite view angle is near nadir. Although MOIDIS is purported to be a 'daily' satellite, near nadir images are available only each 3 to 5 days. The resolution degrades as the sensor view angle increases. Field-scale applications are not possible with the resolution of MODIS. Also, MODIS images do not have a convenient method to preview the data upon image order. In MODIS, a near-nadir cloud-free image is difficult to find since it is often blended into several other "lower quality" images (images having clouds and/or a larger sensor view angles). Also, MODIS images are not always in a usable condition due to hardware/software malfunctioning, and a careful evaluation by the user is required for a quality application. Table 1 briefly summarizes characteristics of MODIS and Landsat images for ET mapping.

Table 1. Characteristics of Landsat and MODIS Satellite Images

Satellite	Landsat 5	MODIS (Terra)
Resolution	30m/120m (shortwave/thermal)	250m-500m/1000m (shortwave/thermal)
Frequency	1image/16days	1 images/1day (2-4 near nadir images/16days)
Field scale application	Usable	Not usable
Regional scale application	Usable	Usable
Higher-level products	Not available	Available
Image previews	Available	Not available
Image quality control	Easy	Difficult

APPLICATION RESULTS AND DISCUSSIONS

In previous studies (Allen et al., 2007b), ET was calculated using Landsat in the western states of Idaho, Utah, California and New Mexico. In this study, 12 MODIS images were selected for application to the Middle Rio Grande region of New Mexico. All selected images were from MODIS Terra, and were near-nadir cloud-free images, and the image dates were chosen to match Landsat images processed during previous studies. Selected MODIS images were then processed and compared with the results of Landsat-based applications.

The largest technical difficulty in applying the METRIC model with MODIS images was the selection of calibration points. In general Landsat applications, the operator selects two extreme "calibration pixels" representing dry and wet agricultural surfaces. The energy balance is internally calibrated based on these calibration pixels by applying information contained in a reference ET calculation (based on the ASCE Penman-Monteith (ASCE-EWRI 2005)) and a FAO-56-based soil water balance-evaporation model (Allen et al., 1998). The thermal resolution of MODIS is 1km, thus, calibration targets should ideally have at least 2km by 2km extent to insure containment of the pixel in the target area. Unfortunately, uniform dry and wet agricultural surfaces of this size are rarely available. In the MODIS application, dry pixels were found from surrounding desert areas, and relative ET for wet pixels was determined from an NDVI-based relationship that was previously established using Landsat-based ET.

Figure 1 shows Landsat (30-120m) and MODIS (500-1000km) based ET maps from a test run in Idaho during July 2003. The snapshot clearly demonstrates that MODIS based energy balance is not applicable for field-scale, while Landsat is applicable atr field-scale where agricultural field sizes are typically large (400m by 400m or more).   The loss of clarity in MODIS images is quite apparent.

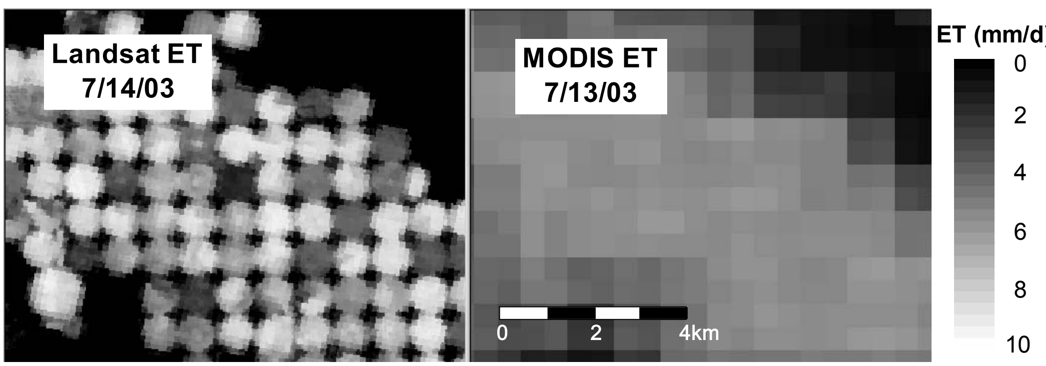

Figure 1. METRIC 24-hour ET by Landsat and by MODIS, for the Same Center-Pivot Irrigated Agricultural Area in Southern Idaho (42^{o}23’ 114^{o}00’)

MODIS ET estimation results were compared with Landsat results in the Middle Rio Grande area of New Mexico, as averages over an extended region and by vegetation group. ET values were compared in terms of alfalfa-referenced crop coefficient (K_c). The result of the comparison is shown in Figure 2 and the summary of the comparison is provided in Table 2. Both the Landsat and MODIS image resolutions were degraded to 2km, in order to avoid any impact of resolution difference on the comparison.

Based on the averages over 12 images, Landsat and MODIS applications calculated similar ET, with an absolute difference in K_c of 0.004. If limited to areas having NDVI 0.5 or higher (NDVI is a vegetation index computed from MODIS bands 1 and 2), the MODIS application slightly underestimated Landsat-based ET on most image dates, possibly because of the unsuccessful internal calibration for the “wet” condition. Results from both satellite applications were similar (0.003 K_c difference) for low vegetated pixels having NDVI 0.2 or lower. Standard deviation of differences between Landsat and MODIS results was about 0.04 in terms of K_C, which indicates that estimation differences for each individual image date were not large. However, discussing estimation accuracy of MODIS application by Landsat for "satellite image dates" is difficult because METRIC applications with Landsat are expected to achieve less than 5 percent error in seasonal ET but may have large error in estimated ET for single dates (Tasumi et al., 2005). The general agreement between Landsat and MODIS indicates that MODIS images have potential for estimating regional ET.

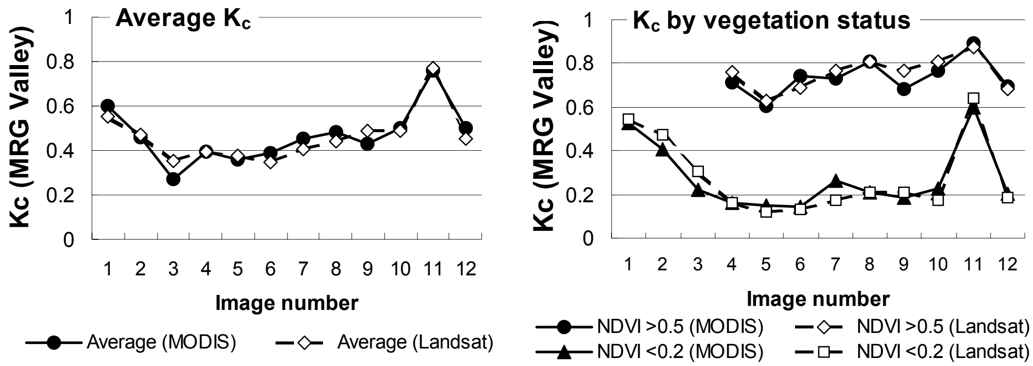

Figure 2. Crop Coefficient (K_c) Estimated by Landsat and MODIS Satellites Averaged over Large Areas of the Middle Rio Grande for 12 images in 2002

Table 2. Comparison of Calculated K_c between Landsat and MODIS.

Image #	Date	MRG valley whole area			MRG valley NDVI >= 0.5			MRG valley NDVI <= 0.2		
		MODIS	Landsat	Difference	MODIS	Landsat	Difference	MODIS	Landsat	Difference
1	1/14/02	0.598	0.555	0.043	-	-	-	0.528	0.543	-0.015
2	3/3/02	0.460	0.470	-0.009	-	-	-	0.409	0.471	-0.061
3	4/4/02	0.272	0.351	-0.079	-	-	-	0.220	0.305	-0.085
4	5/6/02	0.393	0.391	0.001	0.712	0.759	-0.047	0.162	0.162	0.000
5	5/22/02	0.357	0.375	-0.018	0.603	0.627	-0.023	0.147	0.120	0.027
6	6/7/02	0.388	0.349	0.038	0.740	0.686	0.054	0.142	0.133	0.010
7	6/15/02(L) 6/16/02(M)	0.452	0.407	0.046	0.729	0.767	-0.039	0.262	0.174	0.088
8	7/25/02	0.480	0.440	0.040	0.808	0.808	0.000	0.211	0.208	0.003
9	8/10/02	0.428	0.485	-0.057	0.685	0.764	-0.079	0.187	0.211	-0.024
10	8/26/02	0.499	0.487	0.012	0.767	0.808	-0.041	0.225	0.176	0.049
11	9/20/02	0.757	0.768	-0.011	0.895	0.876	0.019	0.600	0.643	-0.044
12	11/6/02 (L) 11/7/02 (M)	0.499	0.451	0.049	0.695	0.685	0.010	0.203	0.187	0.016
Average	-	0.465	0.461	0.004	0.737	0.753	-0.016	0.275	0.278	-0.003
Standard Error	-	-	-	0.042	-	-	0.041	-	-	0.048

SUMMARY AND CONCLUSIONS

In this study, the METRIC ET estimation model was applied with MODIS imagery in New Mexico to evaluate its potential to be applied for ET estimation and water resources management. With the coarse resolution of MODIS (~ 1km thermal resolution), MODIS was found to be unsuitable for field-scale applications, unless some thermal pixel sharpening technique is developed. In project and regional scale applications, MODIS has good potential for ET estimation and water resources management.

MODIS based ET maps were compared with Landsat based results for 12 dates in New Mexico. Average ET between MODIS and Landsat applications were similar (0.004 difference of average Kc), which indicates that MODIS imagery, combined with METRIC, are useful as an ET estimation tool. Future study is required to improve calibration strategies for the energy balance with MODIS imagery.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. UN FAO, Irrig. Drain. Pap. 56. Rome, Italy. 300p.

Allen, R.G., Tasumi, M., Morse, A., and Trezza, R. 2005. A Landsat-based Energy Balance and Evapotranspiration Model in Western US Water Rights Regulation and Planning. J. Irrigation and Drainage Systems. 19:251-268.

Allen, R.G., Trezza, R., and Tasumi, M. 2006. Analytical integrated functions for daily solar radiation on slopes for use in energy balance and evapotranspiration studies. Agricultural and Forest Meteorology (accepted).

Allen, R.G., Tasumi, M., Trezza, R., 2007a. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. J. Irrig. and Drain. Engineering, ASCE, (accepted).

Allen, R.G., Tasumi, M., Morse, A., Trezza, R., Kramber, W., Lorite, I., 2007b. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Applications. J. Irrig. and Drain. Engineering, ASCE, (accepted).

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.

Bastiaanssen,W.G.M., 1995. Regionalization of surface flux densities and moisture indicators in composite terrain. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Bastiaanssen,W.G.M., M.Menenti, R.A.Feddes, and A.A.M.Holtslag, 1998a. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. J. of Hydr. 212-213:198-212.

Bastiaanssen,W.G.M., H.Pelgrum, J.Wang, Y.Ma, J.Moreno, G.J.Roerink and T. van der Wal, 1998b. The Surface Energy Balance Algorithm for Land (SEBAL): Part 2 validation. J. of Hydr. 212-213:213-229.

Bastiaanseen,W.G.M., 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. J. of Hydr. 229:87-100.

Bastiaanssen, W. G. M., Noordman, E. J. M., Pelgrum, H., Davids, G. Thoreson, B. P., 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, ASCE, 131(1):85-93.

Doorenbos, J. Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24, Food and Agricultural Organization of the United Nations, Rome, 179p.

King, M. D., Closs, J., Wharton, S., & Myers, M. (Ed.) (2004). EOS Data Products Handbook Volume 1 (Revised 2004). EOS Project Science Office, NASA Goddard Space Flight Center, Greenbelt, MD.

Knyazikhin, Y., Glassy, J., Privette, J. L., Tian, Y., Lotsch, A., Zhang, Y., Wang, Y., Morisette, J. T., Votava, P., Myneni, R. B., Nemani, R. R., and Running, S. W. 1999. MODIS Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation Absorbed by Vegetation (FPAR) Product (MOD15) Algorithm Theoretical Basis Document. http://eospso.gsfc.nasa.gov/atbd/modistables.html

Morse,A., M.Tasumi, R.G.Allen and W.J.Kramber, 2000. Application of the SEBAL Methodology for Estimating Consumptive Use of Water and Streamflow Depletion in the Bear River Basin of Idaho through Remote Sensing: Final Report. Idaho Department of Water Resources, ID.

Morse,A., R.G.Allen, M.Tasumi, W.J.Kramber, R.Trezza and J.L.Wright, 2001. Application of the SEBAL Methodology for Estimating Evapotranspiration and Consumptive Use of Water Through Remote Sensing: Final Report. Idaho Department of Water Resources, ID.

Tasumi, M., Trezza, R., Allen, R. G.., and Wright, J. L. (2005). “Operational aspects of satellite-based energy balance models for irrigated crops in the semi-arid U.S.” J. Irrigation and Drainage Systems. 19:355-376.

Tasumi, M., Allen, R.G., and Trezza, R., 2007. At-surface reflectance and albedo from satellite for operational calculation of land surface energy balance. J. Hydrol. Engr. ASCE. (submitted)

Vermote, E. F., and Vermeulen, A. (1999). “Atmospheric correction algorithm: spectral reflectances (MOD09).” MODIS Algorithm Theoretical Background Document, 107p. Document available on line at http://modis.gsfc.nasa.gov/data/atbd/atbd_mod08.pdf.

Wan, Z. 1999. MODIS Land-Surface Temperature Algorithm Theoretical Basis Document (LST ATBD) Version 3.3. Institute for Computational Earth System Science, University of California, Santa Barbara, CA.

Wright, J. L. 1981. Crop coefficients for estimates of daily crop evapotranspiration. Irrigation scheduling for water and energy conservation in the 80s, ASAE, Dec. St. Joseph, Mich.

CALIBRATING SATELLITE-BASED VEGETATION INDICES TO ESTIMATE EVAPOTRANSPIRATION AND CROP COEFFICIENTS

Masahiro Tasumi[1]
Richard G. Allen[2]
Ricardo Trezza[3]

ABSTRACT

This paper presents a procedure to estimate actual evapotranspiration (ET) using a satellite-derived vegetation index. Actual ET is computed in a traditional manner using the crop coefficient (K_c) and reference ET (ET_{ref}) procedure (i.e., ET = K_c x ET_{ref}) with K_c estimated from the satellite-based NDVI. This study calibrated relationships between K_c and NDVI using satellite-based ET determined by surface energy balance. This unique approach enables calibration of the K_c vs NDVI equations using large numbers of sampled fields (in this case, more than 3000). Thus the calibration represents a regional average K_c estimate. The study was conducted for alfalfa, beans, sugar beet, corn, potatoes, and small grain crops, which are the major crops in southern Idaho. Estimation accuracy for ET was statistically evaluated. Average error of seasonal ET was within 5 percent of the energy balance (EB) determined ET for most crop types. Error in seasonal ET from individual fields is expected to be within 10 percent. NDVI based ET was compared with lysimeter measurements of ET from grass and sugar beets. The seasonal error of the NDVI based method was only 2 percent for grass and 6 percent for the sugar beets, as compared to lysimeter measurements. Statistical accuracy assessments suggest that NDVI based ET estimation can be a robust, simple and inexpensive tool to estimate ET from irrigated agricultural crops with reasonable good accuracy.

INTRODUCTION

Evapotranspiration (ET) is the major consumptive use of irrigation water and thus, spatial and temporal quantification of ET is important in agricultural water management, especially in areas experiencing scarcity in total fresh water resources. ET has traditionally been estimated at regional and field-scales using the crop coefficient (K_c) method (ASCE - EWRI 2005):

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[1] Associate Professor, University of Miyazaki, 1-1, Gakuen Kibanadai-Nishi, Miyazaki-shi, Miyazaki 889-2192, JAPAN; tasumi@kimberly.uidaho.edu.
[2] Professor, University of Idaho, 3793N, 3600E, Kimberly ID 83341; rallen@kimberly.uidaho.edu.
[3] Visiting Associate Professor, University of Idaho, 3793N, 3600E, Kimberly ID 83341; rtrezza@kimberly.uidaho.edu.

$$ET = K_c \times ET_{ref} \tag{1}$$

where ET_{ref} is reference ET (alfalfa (ET_r) or clipped grass (ET_o) reference).

Using recently developed techniques, accurate ET estimation, spatially and temporally, is possible via satellite-based energy balance (e.g. Anderson et al., 1997; Bastiaanssen et al., 1998; Kustas and Norman, 2000; Allen et al., 2007a). However, this approach requires surface temperature imagery along with a relatively high knowledge level of near-surface energy exchange physics and aerodynamics, which prevents many general water resources professionals from applying the technique. The K_c-based ET estimation method is often preferred for operational applications because of its simplicity (Duchemin et al., 2005). Simpler ET estimation approaches based on correlation of crop ET and NDVI from satellite images have been investigated by Allen et al., (2003), Hunsaker (2003) and Duchemin et al., (2005), where NDVI is the normalized difference vegetation index and is computed from red and near infrared bands of the satellite. While this approach is simple, accuracy of ET estimation can be limited because vegetation indices do not provide information on the soil evaporation portion of ET in irrigated agriculture. Earlier work on K_c vs. NDVI based on aerial imagery included that by Neale et al. (1989) and Bausch et al. (1989).

In this paper, we attempt to determine mean K_c by NDVI, where the NDVI- K_c relationship is calibrated using satellite based energy balance. This approach requires a one-time application of the energy balance for each area of interest to calibrate the local K_c vs NDVI function. Once the K_c is locally calibrated by NDVI, ET for the following years can be estimated with reasonable accuracy as:

$$ET = (a \cdot NDVI + b) \times ET_{ref} \tag{2}$$

where a and b are regional constants calibrated by surface energy balance, NDVI is at-satellite or at-surface NDVI from satellite image, and ET_{ref} is alfalfa or grass reference ET calculated by weather data. Other vegetation indices besides NDVI, for example SAVI, have been explored for estimating K_c. However, it appears that NDVI exhibits a desirable tendency to 'saturate' at about the same leaf area index as does K_c, thus reaching an upper limit at the same time as K_c (Allen et al., 2007c). The 'at-satellite' NDVI (computed with no atmospheric correction to bands) appears to be as consistent in estimating K_c as an at-surface NDVI (Allen et al., 2007c). Satellite based ET maps provide a robust means to analyze K_c, because the method can cover large numbers of sampled fields (Tasumi et al., 2005, Tasumi and Allen, 2006).

METHODOLOGY

ET images and related field data produced by surface energy balance by Tasumi et al. (2005) and Tasumi and Allen (2006) were used to evaluate relationships between alfalfa-reference K_c (K_{cr}) and at-satellite NDVI ($NDVI_{as}$). The study area is the Magic Valley in Idaho, a large irrigated agricultural area in south-central Idaho having a semi-arid climate (Figure 1). The major crops of the area are alfalfa, dry, edible beans, field and sweet corn, small grains, peas, potatoes and sugar beets. Typical field sizes in the region are 400 m by 400 m to 800 m by 800 m, thus, ET from individual fields is amenable to sampling from Landsat images having 30 m by 30 m spatial resolution.

During previous studies, twelve Landsat images from March through October, 2000, were processed for the study area using the METRIC model to estimate ET and K_{cr}. The METRIC program and applications are described in Allen et al, (2007a, b). METRIC K_{cr} was developed for each Landsat image on a 16 to 32 day frequency. K_{cr} values were interpolated between satellite-image dates using a spline function (Excel Cubic Spline 1.01 by SRS1 Software) applied pixel by pixel. A crop-type classification was conducted for the same year using the Landsat images and independent ground truth information. In total 3420 fields were sampled that included eight crop types (Table 1).

Figure 2 shows the $NDVI_{as}$ vs. K_{cr} relationships from March to October. $NDVI_{as}$ vs. K_{cr} relationships tended to be linear and converged after NDVI > 0.7 (i.e. maximum cover season). The general relationships (solid lines) in Figure 2 were drawn past the point of $NDVI_{as}$ vs K_{cr} convergence, and the intercept was determined so that the average estimation error is zero when ET is estimated using equation 2. Using the general calibration developed in Figure 2, equation 2 can be reexpressed as:

$$ET = \left(1.18 \cdot NDVI_{as} + 0.04\right) \times ET_r \qquad (3)$$

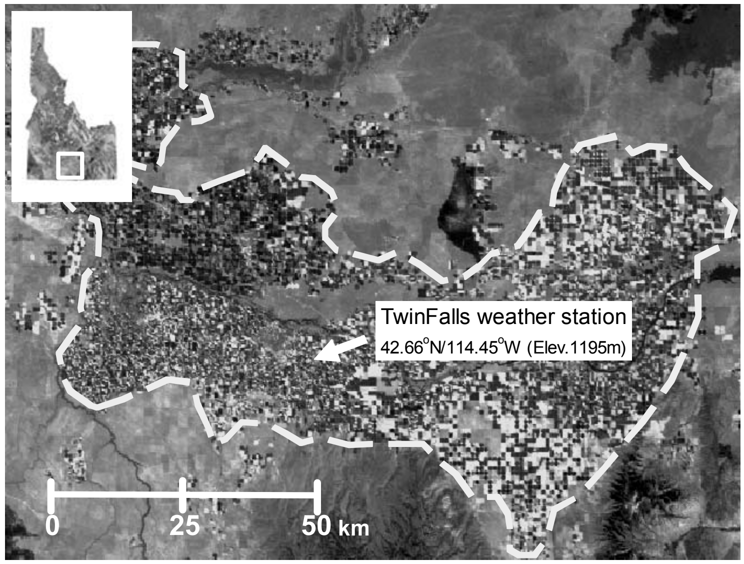


Figure 1. Agricultural Study Area in Magic Valley, Idaho (Circled by Dotted Line) and Location of Weather Station Used to Calculate Reference ET Used as a Basis of the Surface Energy Balance and Derivation of Crop Coefficients

Table 1. Investigated Crops and Numbers of Sampled Fields.

Crop type	Alfalfa	Bean	Corn	Potato(S) *	Potato(L) *	Sugar Beet	Spring Grain	Winter Grain	Total
Sample field number	325	432	451	396	221	495	536	564	3420

* Potato(S) and Potato(L) are potato crops having short (S) and long (L) full cover periods respectively.

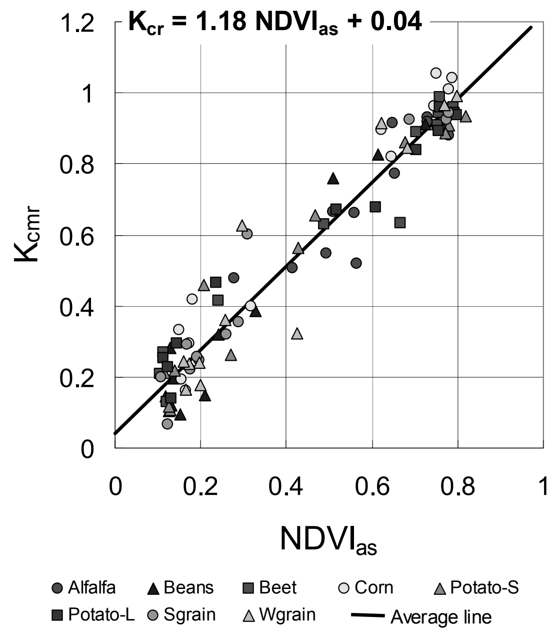


Figure 2. Mean K_{cr} vs. $NDVI_{as}$ by Crop Type from March to October (5 day average).

RESULTS AND DISCUSSION

ET was estimated using equation 3 for the twelve Landsat images of southern Idaho, 2000. Figure 3 shows the result image for 7/5/2000. Figure 4 shows daily ET averaged over multiple fields of sugar beets where ET was estimated using $NDVI_{as}$ and K_{cr}. The ET estimated from $NDVI_{as}$ corresponds well with METRIC results for all evaluated crops.

Seasonal ET was calculated for average field conditions (i.e. using NDVI averaged over all sampled fields having the same crop type) by employing a spline curve to interpolate daily between average NDVI from each Landsat date. Daily ET was calculated by multiplying K_{cr} computed for each day of the season via the spline by alfalfa-reference ET (ET_r) for that day. Seasonal ET was then calculated by summing daily values across the growing season, which in this case was defined as March 15 – October 17 for all crops (these were the first and last dates for Landsat coverage for 2000).

Mean differences between seasonal ET estimated by NDVI and seasonal ET determined directly from METRIC for the same groups of fields are compared in Table 2. Results indicate that, in general, equation 3 estimates ET with reasonable accuracy for the primary crops grown in southcentral Idaho, with average error within 5 percent in most crop types. Also, error of seasonal ET estimation is within 10 percent for most individual fields as compared to ET derived directly from the METRIC energy balance.

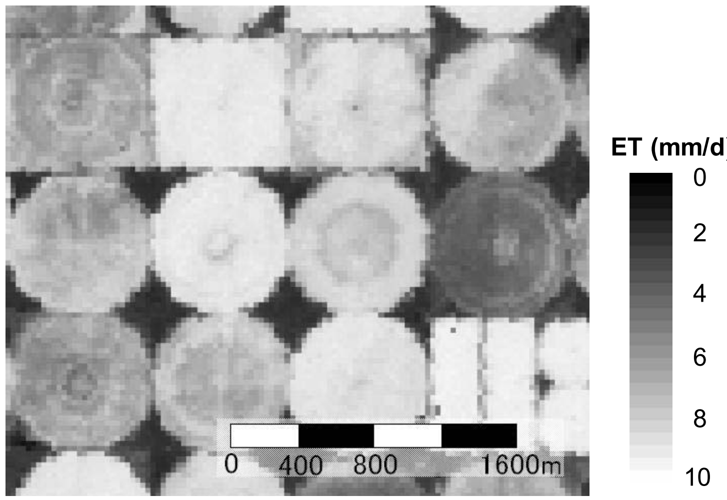


Figure 3. ET Estimated by $NDVI_{as}$ on 7/5/2000, (Landsat 5, path 40, row 30).

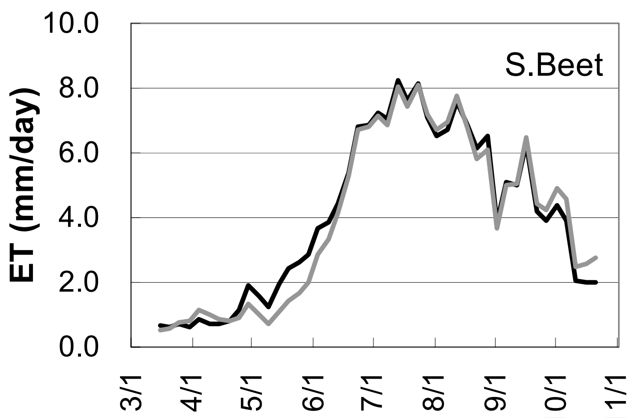


Figure 4. Comparisons Between Daily ET (5-day Mov. Avg.) Determined by METRIC and ET Determined from the General K_{cr} vs. $NDVI_{as}$ Relationship, Averaged Over All Sugar Beet Sampled Fields

Table 2. METRIC Seasonal ET (March 15-October 17) and Error in Seasonal ET Estimated Using NDVI (Averaged Over Multiple Fields of the Same Crop), and Estimation Error for Individual Fields for year 2000

Crops	Alfalfa	Beans	Beet	Corn	Potato(S)	Potato(L)	S.Grain	W.Grain
METRIC ET (mm/season)	1001	479	904	846	733	846	720	837
Average error* (%)	5	7	-2	-7	1	-2	-2	-2
Error range* (%, 1σ)	+1 to +8	0 to +14	-7 to +1	-12 to -2	-3 to +6	-6 to +3	-7 to +3	-8 to +3

* Positive values indicate over estimation by the NDVI-based method. Error range represents differences between seasonal METRIC ET and ET by Eq. 3 for individual fields.

Performance of NDVI based ET estimation was tested at two fields equipped with precision weighing lysimeters near Kimberly, Idaho. The lysimeter ET data were collected by Dr. J.L.Wright at the USDA Agricultural Research Service facility during the 1970's and 1980's (Wright, 1982; Wright, 1991). Daily and seasonal NDVI based ET was estimated for the Lysimeter field from eight clear-sky Landsat 5 images in 1989 (4/18, 5/4, 5/20, 6/5, 6/21, 7/7, 7/23 and 9/25) using equation 3. $NDVI_{as}$ values used in this analysis were averages taken from three pixels near the center of the grassed lysimeter field (i.e. for the center 120m by 30m area), and from four pixels near the center of the sugar beet lysimeter field (i.e. for the center 60m by 60m area). $NDVI_{as}$ computed for each satellite image date was then interpolated for days between dates using a cubic spline function.

The NDVI-based ET estimations corresponded relatively well with the actual lysimeter measurements for both the grass and sugar beet fields. The standard error of daily ET estimates as compared to lysimeter measurements was 0.6 mm d^{-1} and 1.3 mm d^{-1} for grass and sugar beets, respectively. On a seasonal basis, the $NDVI_{as}$-based ET estimates using the general equation developed for southern Idaho using year 2000 date (i.e. equation 3) estimated seasonal ET relatively accurately for the two lysimeter fields during 1989. The estimation error for seasonal ET was 2 percent for grass and 6 percent for sugar beets, both of which were underestimated. The expected error range for grass is unknown, but the observed error for sugar beet was within the expected error range determined in Table 2 (i.e. from 7 percent underestimation to 1 percent overestimation). This comparison study demonstrates a good potential for using NDVI based ET estimates, even for applications to individual fields.

SUMMARY AND CONCLUSIONS

This study developed a simple vegetation index-based equation to estimate total ET via satellite. The empirical NDVI based K_c relationship was calibrated using ET information developed by satellite-based energy balance, so that the calibration represents mean K_c vs. NDVI relationships and conditions over large number of fields (3420 individual agricultural fields). Accuracy of ET estimated using the calibrations is expected to have similar accuracy, when averaged over enough fields to average out differences in ET caused by individual irrigation events, to the original ET maps developed from METRIC.

Alfalfa, beans, sugar beets, corn, two variety groups of potatoes, and spring and winter grains in south-central Idaho were evaluated. Results indicated that one single equation was sufficient to estimate ET for all of the investigated crop types. This means that crop classification is not required to estimate ET via the NDVI-based method, which is a strong advantage and permits low expense and rapid application.

Average error of seasonal ET was within +/-5 percent for most crop types. Error in seasonal ET estimated for any individual field lies within 10 percent in most cases. In the comparison with Lysimeter-measured ET, the seasonal error for the NDVI based method was only 2 percent for grass, and 6 percent for sugar beets.

The statistical assessment of accuracy, including comparisons with actual lysimeter measurements, suggests that NDVI based ET estimation may represent a dependable tool to estimate ET over large areas. Achieving the accuracy levels reported herein using the traditional ET estimation methods without the aid of satellites is difficult. The high accuracy reported herein was achieved partly because the NDVI based ET equation was calibrated to the particular region using ET derived using a reliable energy balance (METRIC). The NDVI based ET approach is empirically based, thus, specific calibration may be necessary for other regions.

REFERENCES

Allen, R. G., Morse, A., and Tasumi, M. 2003. Application of SEBAL for Western US water rights regulation and planning. Proc. ICID Int. Workshop on Remote Sensing, Montpellier, France.

Allen, R.G., Tasumi, M., Trezza, R., 2007a. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. J. Irrig. and Drain. Engineering, ASCE, (accepted).

Allen, R.G., Tasumi, M., Morse, A., Trezza, R., Kramber, W., Lorite, I., 2007b. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Applications. J. Irrig. and Drain. Engineering, ASCE, (accepted).

Allen, R.G., Tasumi, M., Trezza, R., Wright, J.L., Lorite, I., Robison, C.W., Morse, A. 2007c. Satellite-based ET mapping for agricultural water management using NDVI. Agricultural Water Management. (in review).

Anderson, M. C., Norman, J. M., Diak, G. R., Kustas, W. P., and Mecikalski, J. R. 1997. A Two-Source Time-Integrated Model for Estimating Surface Fluxes Using Thermal Infrared Remote Sensing. Remote Sensing of Environment. 60:19.5-216.

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.

Bastiaanssen,W.G.M., M.Menenti, R.A.Feddes, and A.A.M.Holtslag, 1998. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. J. of Hydr. 212-213:198-212.

Bausch, W. C., and Neale, C. M. U. 1989. Spectral Inputs Improve Corn Crop Coefficients and Irrigation Scheduling. Trans. ASAE, 32(6):1901-1908.

Duchemin, B., Hadria, R., Erraki, S., Boulet, G., Maisongrande, P., Chehbouni, A., Escadafal, R., Ezzahar, J., Hoedjes, J. C. B., Kharrou, M. H., Khabba, S., Mougenot, B., Olioso, A., Rodriguez, J.-C., and Simonneaux, V. 2005. Monitoring wheat phenology and irrigation in Central Morocco: On the use of relationships between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. Agricultural Water Management, 79:1:1-27.

Hunsaker, D. J., Pinter, P. J., Jr., Barnes, E. M., and Kimball, B. A. (2003). “Estimating cotton evapotranspiration crop coefficients with a multispectral vegetation index.” Irrig. Sci., 22(2), 95–104.

Kustas, W. P. and Norman, J. M. 2000. A Two-Source Energy Balance Approach Using Directional Radiometric Temperature Observations for Sparse Canopy Covered Surfaces. Agron. J. 92:847–854.

Neale, C. M. U., Bausch, W.C., and Heerman., D. F. 1989. Development of reflectance-based crop coefficients for corn. Trans. ASAE, 32(6):1891-1899.

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, J. Irrig. and Drain. Engrg, ASCE, 131(1), 94-109.

Tasumi, M. and Allen, R. G. 2006. Satellite-based ET mapping to assess variation in ET with timing of crop development. Agricultural Water Management (accepted).

Wright, J. L. 1982. New evapotranspiration crop coefficients. Journal of Irrigation and Drainage 108:57-74.

Wright, J. L. 1991. Using weighing lysimeters to developed evapotranspiration crop coefficients. Proceeding of the International Symposium on Lysimetry, Honolulu, Hawaii, ASAE.

REDUCING OGALLALA WITHDRAWALS BY CHANGING CROPPING AND IRRIGATION PRACTICES IN THE TEXAS HIGH PLAINS

Paul D. Colaizzi[1]
Prasanna H. Gowda[2]
Thomas H. Marek[3]
Dana O. Porter[4]

ABSTRACT

Irrigated crop production in the Texas High Plains is dependent on the Ogallala Aquifer, which has declined by up to 50 percent in some areas since irrigation development began in the 1930-40s. About 6.5 million acre-feet (ac-ft) of water was pumped to irrigate 4.6 million acres in 2000, with most irrigation demand being for corn and cotton production. Cotton is produced primarily in the Southern Texas High Plains, with corn and winter wheat comprising most of the irrigated area in the Northern Texas High Plains. However, cotton production is expanding northward again and replacing corn in some areas because both crops currently have similar revenue potential but cotton has about half the irrigation water requirement, and may result in profitable yields under dryland and deficit irrigated conditions. In the Northern Texas High Plains, combined annual irrigation demand for corn and cotton could be reduced from 2.6 to 2.0 million ac-ft by replacing 50 percent of the irrigated corn area with cotton, and combined irrigation demand could be reduced to 1.6 million ac-ft if cotton irrigation applications were reduced to 50 percent of full crop evapotranspiration minus rainfall. In the Southern Texas High Plains, annual irrigation demand for cotton could be reduced from 1.4 to 1.0 million ac-ft if overall irrigations were reduced to 50 percent of full crop evapotranspiration minus rainfall. Deficit irrigation results in some yield penalty; however, if the crop is relatively drought tolerant, this may be offset somewhat by the reduced energy costs of pumping.

INTRODUCTION

The semi-arid Texas High Plains is a major producer of irrigated and dryland crops and comprises the southern portion of the U.S. Great Plains. Irrigation

[1] Agricultural Engineer, USDA-ARS Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012; pcolaizzi@cprl.ars.usda.gov.
[2] Agricultural Engineer, USDA-ARS Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012; pgowda@cprl.ars.usda.gov.
[3] Senior Research Engineer, Texas Agricultural Experiment Station, Texas A&M University, 6500 Amarillo Blvd W, Amarillo, TX 79106; t-marek@tamu.edu.
[4] Extension Agricultural Engineer, Texas Cooperative Extension and Texas Agricultural Experiment Station, Texas A&M University, 1102 E. FM 1294, Lubbock, TX 79403; d-porter@tamu.edu.

typically results in doubled to quadrupled crop yields compared to dryland production levels, making irrigated agriculture a vital component of the regional economy (Howell, 2001). Large-scale irrigation first became practical in the 1930-40s when internal combustion engines, turbine pumps, right-angle gear drives, and rotary well drilling became available for pumping groundwater (Musick et al., 1988). Irrigation accelerated during the major drought in the 1950s, peaking at around 6.0 million acres in 1974, and declined thereafter to 4.0 million acres in the Texas High Plains by 1989 (Musick et al., 1990).

Nearly all irrigation in the Texas High Plains was developed solely from the Ogallala (High Plains) Aquifer as surface water resources are inadequate for this purpose. The Ogallala underlies parts of eight states (South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas) and is one of the largest freshwater aquifers in the world. Over 90 percent of Ogallala withdrawals in the Texas High Plains are for irrigation; however, the Ogallala is essentially a closed basin and withdrawals have greatly exceeded recharge, resulting in severe decline of groundwater levels since irrigation development began. In some areas, more than 50 percent of the predevelopment saturated thickness has been pumped, and groundwater levels have dropped over 150 ft (McGuire, 2003). However, the combination of greater lift requirements, increasing unit energy costs, and relatively static commodity prices led to overall reductions in pumping rates after 1974, and rates of aquifer decline have abated in many areas. Increases in pumping energy costs will continue to affect upper limits in aquifer withdrawal rates and therefore crop productivity. These factors threaten the long-term economic viability of irrigated agriculture in the Texas High Plains.

The purpose of this paper is to explore the potential for reducing withdrawals from the Ogallala Aquifer by changing cropping patterns (i.e., conversion from corn to cotton) and reducing irrigation pumping for relatively drought-tolerant crops (i.e., cotton, grain sorghum, and wheat), where no net loss in irrigated land area is assumed. Specific objectives are (a) review recent irrigation inventories and practices in the Texas High Plains; (b) estimate irrigation demand by crop based on typical application fractions relative to evapotranspiration and precipitation; (c) estimate potential reductions in irrigation demand by converting fully irrigated corn to cotton for a range of cotton irrigation application fractions; and (d) examine the trade-off between reductions in irrigation demand (through deficit irrigation) and crop productivity. An economic analysis is presently beyond the scope of this paper; however, it is anticipated that the results presented herein will be useful in foreseen adoption rates and in long-term regional water resources planning.

STUDY AREA

The study area is in the Texas High Plains, which is defined as the 39-county area comprising the Texas Agricultural Statistics Service (TASS) Districts 11

(Northern High Plains) and District 12 (Southern High Plains) (Fig. 1). These districts generally overlie the Ogallala Aquifer in Texas. The Canadian River roughly bisects portions of the Ogallala Aquifer in the Northern District. Elevations above mean sea level (MSL) range from approximately 2,500 ft along the eastern boundaries to over 4,000 ft toward the northwest. The region is mostly semi-arid, with extremely variable precipitation (both temporally and spatially, averaging 16 to 22 inches west to east, respectively). The region also has high evaporative demand due to high solar radiation, high vapor pressure deficit, and strong regional advection. Soils are generally described as moderately permeable in the Southern District, slowly permeable in the Northern District south of the Canadian River, and a mix north of the Canadian River (Musick et al., 1988). Corn and wheat have traditionally been produced north of the Canadian River, with cotton being produced further south, although cotton has recently expanded northward into the corn-producing areas, which will be discussed further.

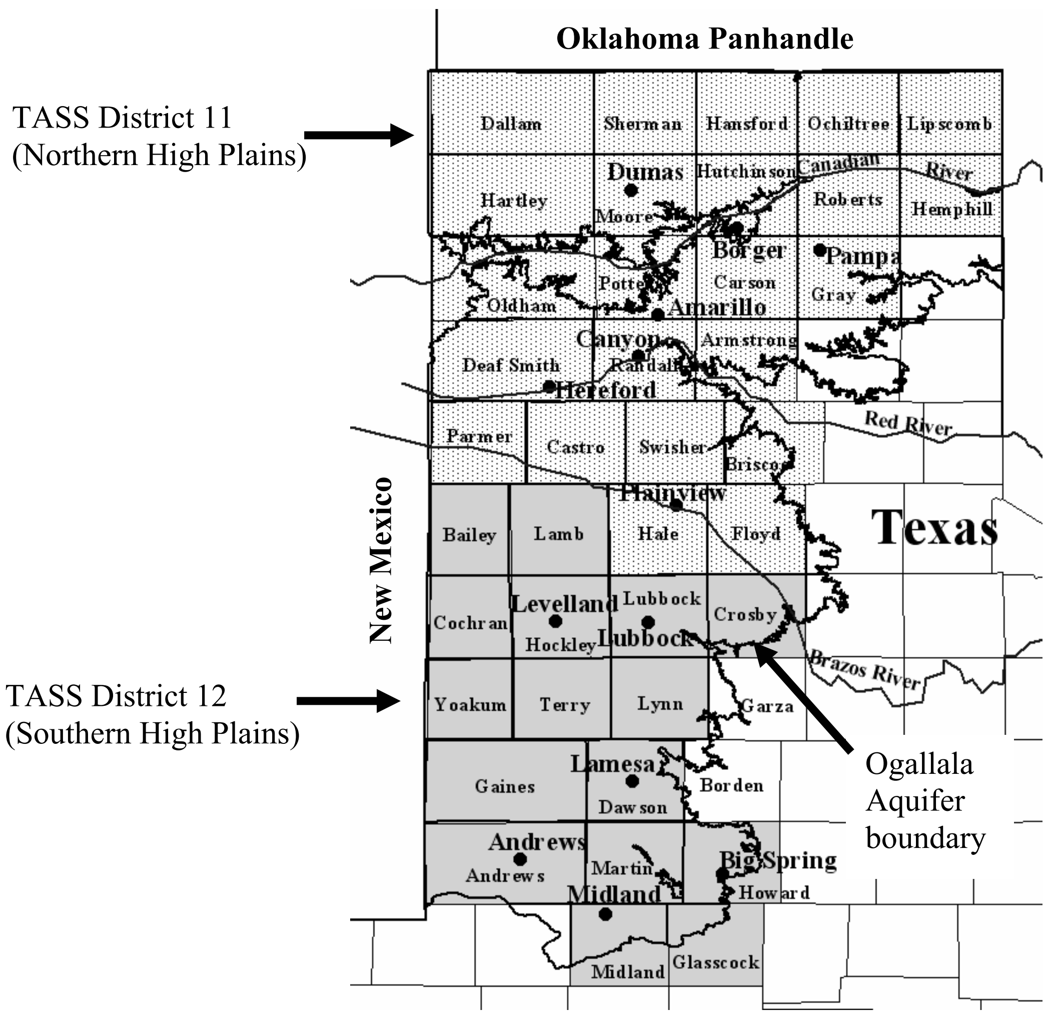


Figure 1. Study area.

IRRIGATION INVENTORY AND PRACTICES

Cropped and irrigated area data were obtained from the Texas Agricultural Statistics Service (TASS, 2006), and the Texas Water Development Board (TWDB, 2001). The TWDB has conducted irrigation surveys in Texas in cooperation with the Natural Resource Conservation Service and the Texas State Soil and Water Conservation Board about every five years since 1958; the most recent was in 2000. From the 2000 survey, the counties in the TASS Northern and Southern High Plains Districts contained a total of 4.6 million irrigated acres (Table 1). This is greater than 4.0 million irrigated acres estimated for approximately the same area (41 counties) in 1989 as reported by Musick et al. (1990), and it appears that total irrigated land area has somewhat stabilized after the 1974 to 1989 decline. About 6.5 million acre feet of water was pumped for irrigation in 2000, with an average depth of 16.9 inches pumped per acre, which was much greater than 4.5 million acre feet (13.5 inches per acre) reported for 1989 (Musick et al., 1990; and verified using 1989 survey data in TWDB, 2001). This was surprising in that it contradicts the general premise of declining irrigation pumping rates, and is likely the result of intensifying drought during the 1990s.

Table 1. Texas High Plains irrigation inventory, 2000 (TWDB, 2001).

TASS District	Drip (ac)	Sprinkler (ac)	Gravity (ac)	Total (ac)	Irrig. Use (ac-ft)	Avg. Depth (in)
11 (NHP)	1,300	1,855,700	937,400	2,794,300	4,164,200	17.9
	0.05%	66.4%	33.5%			
12 (SHP)	20,600	1,487,600	324,000	1,832,100	2,340,500	15.3
	1.12%	81.2%	17.7%			
Total	21,900	3,343,200	1,261,300	4,626,400	6,504,700	16.9
	0.47%	72.3%	27.3%			

Irrigation technology consisted of about 72 percent sprinkler (nearly all mechanically-move center pivot systems), 27 percent gravity (mostly graded furrow), and less than 0.5 percent drip (mostly subsurface drip irrigation, or SDI). The proportion of sprinkler irrigation has increased significantly from 44 percent in 1989 (Musick et al., 1990). In 2000, most of the drip area was in the Southern High Plains (20,600 ac) where cotton is primarily produced, but severe drought, declining water resources, increasing energy costs, and favorable cotton response under SDI prompted rapid expansion, with some estimates up to 250,000 ac by 2004 (J. Bordovsky, pers. communication). Preliminary data at Bushland, TX suggest that cotton fiber quality was better under SDI compared with sprinkler methods (Colaizzi et al., 2005), and SDI has been shown to enhance yield under very limited irrigation relative to sprinkler methods for a variety of crops and locations (Colaizzi et al., 2006). For these reasons and as cotton production expands in the Northern Texas High Plains, SDI may see even greater adoption in the near future.

Gross seasonal irrigation depths (I_d) applied to various crops in the Northern Texas High Plains were documented by the Texas Cooperative Extension AgriPartners program, which includes several hundred on-farm demonstrations of irrigation management based on crop evapotranspiration (ET_c) with cooperating producers (Table 2; New, 2003). I_d ranged from 8 in. for center pivot (CP)-irrigated winter wheat to 29 in. for gravity (surface)-irrigated grain corn; these were derived from totalizing flow meters (usually at the well head). ET_c data used in irrigation scheduling were disseminated to producers by the Texas High Plains Evapotranspiration Network (TXHPET; Howell et al., 1998a; Porter et al., 2005), which presently has seventeen agricultural weather stations at strategic sites in the Northern and Southern Texas High Plains. The TXPHET Network computes ET_c as

$$ET_c = ET_{os}K_c \qquad (1)$$

where ET_{os} is the ASCE-Standardized Penman-Monteith equation for a grass reference (Allen et al., 2005) and K_c is the crop coefficient, which reflects both transpiration and evaporation under fully irrigated conditions. The K_c functions were developed at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas, where large precision weighing lysimeters have measured water use of major irrigated crops in the region since 1987 (Evett et al., 2000; Howell et al., 1995; 1997b; 1998b; 2004; Steiner et al., 1991). The K_c functions are based on cumulative growing degree days (a.k.a. heat units), which are based on crop-specific minimum and maximum air temperature thresholds (e.g., Peng et al., 1989).

Table 2. Average gross irrigation depths, irrigation rates, and crop production of producers participating in AgriPartners Program, 1998-2002 (New, 2003).

Crop	CP I_d (in.)	Avg. FR (eq. 2)	Avg. CP Irrigation Production		Grav. I_d (in.)	Avg. FR (eq. 2)	Avg. Gravity Irrigation Production	
Grain corn	22	0.84	184	bu/ac	29	1.11	170	bu/ac
Silage corn	21	0.80	26	ton/ac	20	0.76	19	ton/ac
Cotton	12	0.90	940	lbs/ac	7	0.64	642	lbs/ac
Peanuts	20	1.48	4000	lbs/ac				
Grain sorghum	12	0.73	102	bu/ac	16	0.98	124	bu/ac
Soybeans	15	0.89	55	bu/ac	13	0.77	48	bu/ac
All wheat	8	0.49	67	bu/ac	10	0.62	75	bu/ac

I_d recorded by the AgriPartners program were generally less than the full irrigation requirement (ET_c minus effective precipitation). This was quantified in Table 2 as the application fraction of the full seasonal irrigation requirement (FR):

$$FR = \frac{I_d}{ET_{c-s} - P_s} \qquad (2)$$

where I_d is the gross seasonal irrigation applied, $ET_{c\text{-}s}$ is the seasonal crop evapotranspiration, and P_s is the seasonal precipitation, with all terms in units of depth (in.). FR is usually a trade-off between the irrigation system capacity (or well capacities) and irrigated area, which is often dictated by the drought sensitivity and price of the crop. FR also reflected expected rainfall, availability of stored soil water, type of irrigation system and system losses (e.g., wind drift, evaporation, runoff), and other operational constraints (e.g., soil permeability, labor availability, pump efficiency, energy costs, etc.). Average FR from AgriPartners data ranged from 0.49 for center pivot-irrigated winter wheat to 1.48 or center pivot-irrigated peanuts (Table 2). Grain yield response of winter wheat greatly diminishes for FR exceeding 0.50 (Schneider and Howell, 1997; 2001); hence a 0.49 FR probably represents optimal irrigation management. The relatively high FR for peanuts reflects that the soil surface must be maintained in a relatively moist condition during the pegging stage, which is not accounted for in K_c.

IRRIGATION DEMAND BY CROP

Estimates of the relative irrigation demand for each crop provided the rationale for examining certain changes in cropping patterns and FR, and hence their potential impact for reducing aquifer withdrawals. Data on irrigation water pumped by crop were not available; instead, irrigation demand by crop was estimated based on crop evapotranspiration, precipitation, irrigated crop area, and FR observed in the AgriPartners program, which were assumed to represent general irrigation practices given the constraints on pumping in the region. For each crop, irrigation demand in 2000 was estimated by

$$I_{v-i} = \frac{1}{12} \sum_{j=1}^{m} \sum_{k=1}^{n(j)} \left(ET_{c-ij} - P_k \right) FR_{ik} A_{ik} \qquad (3)$$

where I_v is the irrigation demand volume (ac-ft), ET_c is the crop evapotranspiration (in.) from equation 1, P is seasonal precipitation (in.), FR is the fraction of the full seasonal irrigation requirement (in.) from equation 2, A is the irrigated area (ac), *i* is the crop, *j* is the TXHPET station, *k* is the county, and *n(j)* is the total number of counties assigned to TXHPET station *j*. About 70 percent of annual precipitation in the Texas High Plains occurs during the growing season (May to September) in a bimodal pattern, with rainfall concentrated around planting and later in the season for summer crops. Some off-season precipitation stored in the soil profile will likely compensate for in-season P_k losses that are difficult to determine (e.g., runoff, evaporation, deep percolation) in equation 3. From Table 2, the FR for a given crop varied by the type of irrigation system used (i.e., center pivot or gravity), and the proportion of irrigation system type used varied by county (TWDB, 2001). Therefore, the FR for crop (*i*) in equation 3 was weighted by county (*k*):

$$FR_{ik} = \theta_{DRIP-k} FR_{DRIP-i} + \theta_{CP-k} FR_{CP-i} + \theta_{GRAV-k} FR_{GRAV-i} \quad (4)$$

where θ is the fractional area of irrigation system type used in county *k*, and FR for each crop and type of irrigation system was taken from Table 2 (DRIP = drip, CP = Center Pivot, GRAV = Gravity). Since the proportion of drip irrigation was relatively small (Table 1) and FR_{DRIP-i} data were lacking, it was assumed that $FR_{DRIP-i} = FR_{CP-i}$.

Irrigated crop area by county in 2000 (and corresponding irrigated + dryland totals) was provided by the Texas Agricultural Statistics Service (TASS, 2006), and summed for the Northern and Southern Texas High Plains Districts (Tables 3 and 4, respectively). Roughly half of the total cropped area was irrigated. Cotton, grain corn, and wheat comprised about 88 percent of the total irrigated area in the Northern High Plains, whereas cotton comprised 79 percent of the total irrigated area in the Southern High Plains. Total irrigated area summed to nearly 4.3 million acres for both districts (Table 3), which is less than 4.6 million acres estimated for 2000 by the TWDB irrigation survey (Table 1), but still greater than 4.0 million acres reported for 1989. The small discrepancy between TASS and TWDB total irrigated area may be due to minor irrigated crops not reported in TASS data (e.g., fresh market vegetables, orchards, or pasture).

With irrigated crop area by county known, irrigation demand was estimated using equation 3. Total irrigation demand for the Northern and Southern Texas High Plains was about 3.5 and 1.9 million ac-ft (Tables 3 and 4, respectively) or a total of 5.4 million ac-ft. Grain corn represented most of the irrigation demand in the Northern Texas High Plains, followed by cotton, whereas cotton represented most demand in the Southern Texas High Plains, followed by peanuts. The average application depths for the Northern and Southern Texas High Plains were 16.3 and 13.1 inches, respectively (Tables 3 and 4, respectively). These were less than the average depths computed using TWDB data (17.9 and 15.3 inches, respectively; Table 1), possibly suggesting that overall FR in the Texas High Plains was greater than FR for producers who participated in AgriPartners. On the other hand, the overall average depth for the Texas High Plains was 15.0 in. (Table 4), which was considerably greater than the TWDB 13.5-in. average for 1989. Despite some uncertainty in *absolute* irrigation demand estimates, the *relative* demand of each crop clearly shows that reducing the irrigation demand for corn and cotton will likely have the greatest immediate impact in reducing Ogallala withdrawals, with several other strategies considered next.

Table 3. Irrigated crop inventory and estimated irrigation demand (I_v) in 2000 for TASS District 11 (Northern Texas High Plains).

Crop	Total Cropped Area (ac)	Irrig. Area (ac)	Irrig. Area (%)	Est. Irrig. Demand (ac-ft)	Avg. Depth (in.)
Grain corn	842,300	825,500	98%	1,864,500	27.1
Silage corn	59,000	48,500	82%	96,800	24.0
Cotton	912,400	767,800	84%	713,500	11.2
Peanuts	2,100	2,000	95%	4,000	24.0
Grain sorghum	697,000	199,000	29%	266,700	16.1
Soybeans	78,000	70,000	90%	109,700	18.8
All wheat	1,930,000	657,500	34%	438,300	8.0
Totals for NHP	4,520,800	2,570,300	57%	3,493,500	16.3

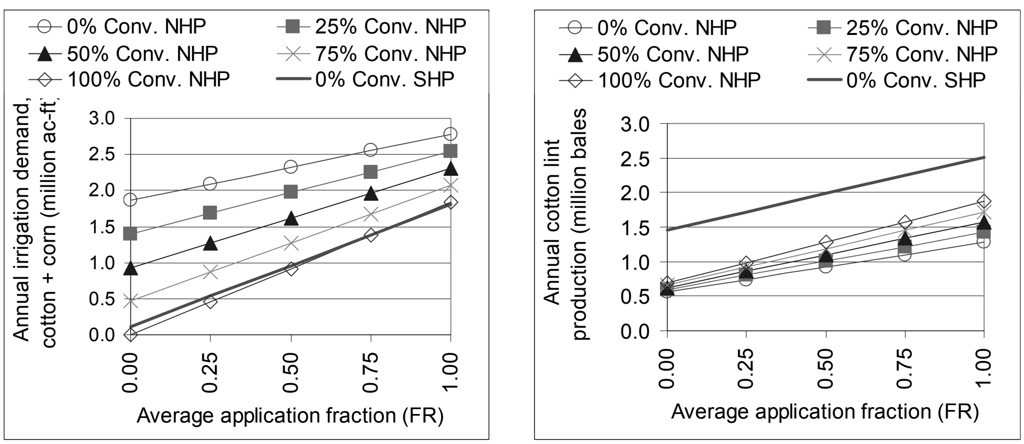
Table 4. Irrigated crop inventory and estimated irrigation demand (I_v) in 2000 for TASS District 12 (Southern Texas High Plains).

Crop	Total Cropped Area (ac)	Irrig. Area (ac)	Irrig. Area (%)	Est. Irrig. Demand (ac-ft)	Avg. Depth (in.)
Grain corn	48,700	47,700	98%	107,500	27.0
Silage corn	11,000	7,200	65%	12,100	20.2
Cotton	2,967,000	1,370,000	46%	1,384,100	12.1
Peanuts	189,000	149,200	79%	243,300	19.6
Grain sorghum	379,000	37,900	10%	37,400	11.8
Soybeans	7,900	7,700	97%	10,600	16.5
All wheat	460,000	109,100	24%	85,100	9.4
Totals for SHP	4,062,600	1,728,800	43%	1,880,100	13.1
NHP + SHP	8,583,400	4,299,100	50%	5,373,600	15.0

CONVERSION FROM CORN TO DEFICIT-IRRIGATED COTTON

Cotton production has recently expanded northward into areas where corn was traditionally produced in the Texas High Plains. The northern extent of cotton production was limited to the area around Hereford, TX (Fig. 1) until 1998, thereafter expanding to south western Kansas. Both crops have similar revenue potential, but maximum cotton yields are possible with about half the irrigation relative to corn; furthermore, profitable cotton yields are possible with limited (deficit) irrigation, unlike corn (Schneider and Howell, 1998; Howell et al., 2004). Although it appears recent cotton varieties require less heat units to reach adequate maturity, there is still inherent risk in producing cotton in a thermally-limited climate. Esparza et al. (2006) computed probabilities of accumulated heat units for cotton (60°F base temperature) for the 131 counties overlying the Ogallala Aquifer in Colorado, Kansas, New Mexico, Oklahoma, and Texas. They estimated a potential water savings of nearly 0.9 million ac-ft if 50 percent of the irrigated corn area was converted to cotton in counties receiving at least 1,800°F-days heat units on average. Of course, additional water savings could be realized with deficit irrigation, provided reductions in yield could be offset by reduced input costs of irrigation so as to maintain farm profitability.

Annual irrigation demand of cotton and corn was estimated in the Northern and Southern Texas High Plains for various irrigated corn-to-cotton area conversions (0 to 100%, Northern High Plains only since little corn is grown in the Southern High Plains), and for various application fractions of the full irrigation requirement (0.0 ≤ FR ≤ 1.0). In the Northern Texas High Plains, corn plus cotton irrigation demand in 2000 was estimated at 2.6 million ac-ft (Table 3). If 50 percent of irrigated corn was converted to cotton, corn plus cotton irrigation demand would be reduced to 2.0 million ac-ft, and if FR for cotton were then reduced to 0.50, corn plus cotton irrigation demand might be reduced to 1.6 million ac-ft (Fig. 2a).



a) b)

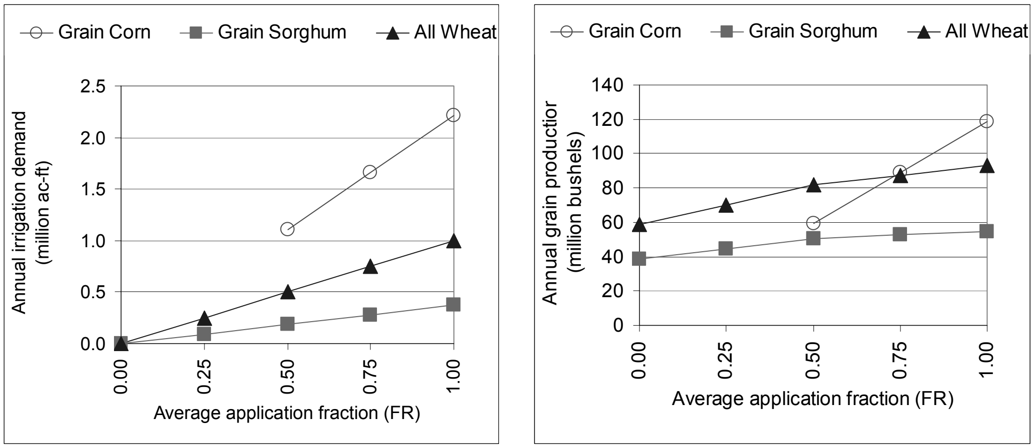
Figure 2. a) Estimated irrigation demand for cotton plus corn when the corn-to-cotton converted area and cotton FR are varied; b) corresponding total (irrigated + dryland) cotton lint production.

The resulting cotton lint production corresponding to irrigation demand was also estimated (Fig. 2b), where the baseline lint production was derived from 2000-04 county averages reported by TASS (2006). The relationship between crop productivity and crop water use (and irrigation applied) has been well-documented for the major irrigated crops in the High Plains. Production functions vary widely for the same crop under different seasons and locations; however, they are often significantly linear for numerous crops, including cotton (Wanjura et al., 2002; Bordovsky and Porter, 2003; Howell et al., 2004; Colaizzi et al., 2005). Also, yield vs. FR can be described fairly well by a single linear function for different seasons and locations. In the Northern Texas High Plains, annual cotton lint production was 1.28 million bales (2000-04 average) for no corn-to-cotton conversion, but this would increase to 1.57 million bales if 50% of irrigated corn was converted to cotton. If FR was then decreased to 0.50, lint production would be reduced to 1.10 million bales. Cotton lint production was greater in the Southern Texas High Plains even if all irrigated corn was converted to cotton in the Northern Texas High Plains.

DEFICIT IRRIGATION OF GRAIN CROPS

Corn, grain sorghum, and winter wheat are the major grain crops irrigated in the Texas High Plains. Only grain sorghum and winter wheat currently produce profitable yields under dryland or deficit irrigated conditions (Schneider and Howell, 1995; 1997; 2001; Colaizzi et al., 2004), whereas dryland corn will produce little or no grain yield (Schneider and Howell, 1998; Howell et al., 1997a). Grain sorghum was extensively irrigated in the Northern Texas High Plains during the 1960s, but has been increasingly converted to dryland (Musick et al., 1990), and irrigated area was only 29 percent of the total grain sorghum area by 2000 (Table 3).

Annual irrigation demand (Fig. 3a) and resulting total (irrigated plus dryland) grain production (Fig. 3b) for corn, grain sorghum, and all wheat were estimated for various FR in a manner similar to cotton (except FR for corn was not estimated below 0.50 due to its relative sensitivity to water shortages). Grain production for grain sorghum and winter wheat (Fig. 3b) was estimated based on two separate linear functions in order to account for a yield plateau sometimes observed around FR = 0.50 (Schneider and Howell, 1995; 1997; 2001; Colaizzi et al., 2004). Corn had a much greater potential for water savings compared with grain sorghum or winter wheat (Fig. 3a), but this came at the greatest expense in grain production (Fig. 3b). Efforts in improving water use efficiency of corn in conjunction with deficit irrigation will likely have the greatest impact in reducing Ogallala withdrawals, provided, of course, some level of farm profitability can be maintained. In the Northern Texas High Plains, these efforts will most likely fit into the agronomic, engineering, and managerial categories discussed by Howell (2001). Some examples include developing more drought-tolerant crop varieties, enhancing precipitation capture and reducing evaporative losses through tillage and residue management, adoption of irrigation systems with greater application efficiency and distribution uniformity, and demand-based irrigation management based on feedback systems (e.g., Peters and Evett, 2004).



a) b)

Figure 3. a) Estimated irrigation demand for varying FR of grain corn, grain sorghum, and all wheat; b) corresponding total (irrigated + dryland) grain production.

CONCLUSION

Irrigated agriculture continues to be a vital component of the economy in the Texas High Plains, but is faced with declining groundwater resources from the Ogallala Aquifer. As of 2000, about 4.6 million acres were irrigated in the 39-county area comprising the Northern and Southern Texas High Plains, with 6.5 million acre-feet of irrigation water being pumped according to Texas Water Development Board data. This was greater than 1989, when 4.0 million acres was irrigated with 4.5 million acre-feet of water, and likely due to intensifying drought during the 1990s. The proportion of gravity, sprinkler (mostly center pivot), and drip (mostly subsurface drip for row crops) was 72, 27, and less than 0.5 percent, respectively, with the vast majority of drip being in the Southern Texas High Plains where cotton is primarily produced. Most irrigation demand estimated in the Northern Texas High Plains was for grain corn (54 percent), followed by cotton (20 percent); in the Southern Texas High Plains, most demand was for cotton (74 percent), followed by peanuts (13 percent).

Conversion from corn to cotton in the Northern Texas High Plains, and deficit irrigation management of cotton in both the Northern and Southern Texas High Plains will likely have the greatest immediate impact in reducing Ogallala Aquifer withdrawals while maintaining acceptable economic returns. This is provided, of course, that international markets are favorable for U.S. cotton, and also that regulations are developed by local water districts to limit new irrigation expansion. Deficit irrigation management of corn could also have significant impact; however, corn is relatively sensitive to water stress, so deficit irrigation is not as feasible without improvements in water use efficiency through agronomic, engineering, and managerial efforts. The market for corn produced in the Texas High Plains is primarily fed cattle, which is expected to increase during the next decade and appears less volatile than cotton. Increased deficit irrigation management of grain sorghum and winter wheat will have the least impact in reducing irrigation water use because these crops are already produced mostly under dryland conditions, and the relatively small irrigated areas are seldom fully irrigated.

REFERENCES

Allen, R. G., I. A. Walter, R. L. Elliott, T. A. Howell, D. Itenfisu, M. E. Jensen, and R. L. Snyder. 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. Am. Soc. Civil Engr., Reston, VA.

Bordovsky, J. P., and D. Porter. 2003. Cotton response to pre-plant irrigation level and irrigation capacity using spray, LEPA, and subsurface drip irrigation. Presented at the 2003 ASAE International Meeting, Las Vegas, NV, 27-30 July. ASAE Paper No. 032008.

Colaizzi, P. D., A. D. Schneider, S. R. Evett, and T. A. Howell. 2004. Comparison of SDI, LEPA, and spray irrigation performance for grain sorghum. *Trans. ASAE* 47(5): 1477-1492.

Colaizzi, P. D., S. R. Evett, and T. A. Howell. 2005. Cotton production with SDI, LEPA, and spray irrigation in a thermally-limited climate. CD-ROM. Irrigation Association Annual Meeting, 6-8 Nov, Phoenix, AZ.

Colaizzi, P. D., F. R Lamm, T. A. Howell, and S. R. Evett. 2006. Crop production comparison under various irrigation systems. In *Proc. Central Plains Irrigation Conference*, Colby, KS., Feb. 21-22, 2006. Available from CPIA, 760 N. Thompson, Colby, KS. pp. 189-207 (Invited).

Esparza, A., P. H. Gowda, R. L. Baumhardt, and C. A. Robinson. 2006. Climatic risk to cotton production in the Ogallala Aquifer region. In *Proc. ASCE-EWRI World Water and Environmental Resources Congress 2005*, 21-25 May, Omaha, NE.

Evett, S. R., Howell, T. A., Todd, R. W., Schneider, A. D., and Tolk, J. A. (2000). Alfalfa reference ET measurement and prediction. In *Proc. 4th Dec. Nat. Irrig. Symp.* (Evans, R. G., Benham, B. L., and Trooien, T. P., eds.). 14-16 Nov. Phoenix, AZ, 266-272.

Howell, T. A., Steiner, J. L., Schneider, A. D., and Evett, S. R. 1995. Evapotranspiration of irrigated winter wheat Southern High Plains. *Trans. ASAE* 38(3):745-759.

Howell, T. A., A. D. Schneider, and S. R. Evett. 1997a. Subsurface and surface microirrigation of corn: Southern High Plains. *Trans. ASAE* 40(3): 635-641.

Howell, T. A., J. L. Steiner, A. D. Schneider, S. R. Evett, and J. A. Tolk. 1997b. Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn: Southern High Plains. *Trans. ASAE* 40(3): 623-634.

Howell, T. A., T. H. Marek, L. L. New, and D. A. Dusek. 1998a. Weather network defends Texas water tables. *Irrig. Business and Tech.* VI(6): 16-20.

Howell, T. A., Tolk, J. A., Schneider, A. D., and Evett, S. R. 1998b. Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity. *Agron. J.* 90(1): 3-9.

Howell, T. A., S. R. Evett, J. A. Tolk, and A. D. Schneider. 2004. Evapotranspiration of full-, deficit-irrigation, and dryland cotton on the Northern Texas High Plains. *J. Irrig. Drain. Engrg., Am. Soc. Civil Engrgs.* 130(4): 277-285.

Howell, T. A. 2001. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* 93(2): 281-289.

McGuire, V. L. 2003. Water-level changes in the High Plains Aquifer, predevelopment to 2001, 1999 to 2000, and 2000 to 2001. USGS Fact Sheet FS-078-03.

Musick, J. T., F. B. Pringle, and J. J. Walker. 1988. Sprinkler and furrow irrigation trends – Texas High Plains. *Appl. Eng. Agric.* 4(1): 46-52.

Musick, J. T., F. B. Pringle, W. L. Harman, and B. A. Stewart. 1990. Long-term irrigation trends - Texas High Plains. *Appl. Eng. Agric.* 6(6): 717-724.

New, L. L. 2003. Agripartner irrigation result demonstrations, 2002. *Texas Coop. Ext.,* Available at: http://amarillo.tamu.edu/programs/agripartners/Irrigation/ irrigation.htm (accessed 13 April 2006).

Peng, S., D. R. Krieg, and S. K. Hicks. 1989. Cotton response to accumulated heat units and soil water supply. *Field Crops Res.* 19:253-262.

Peters, R.T., and S.R. Evett. 2004. Complete center pivot automation using the temperature-time threshold method of irrigation scheduling. Meeting Paper No. 042196 In: Proceedings of the ASAE/CSAE Annual International Meeting. August 1-4, 2004, Ottawa Canada.

Porter, D. O., T. H. Marek, T. A. Howell, and L. L. New. 2005. The Texas High Plains Evapotranspiration Network (TXHPT) User Manual v. 1.01. Texas A&M University Agricultural Research and Extension Center Rep. 03-37. Available at: http://txhighplainset.tamu.edu/usermanual.pdf (accessed 20 April 2006).

Schneider, A. D., and T. A. Howell. 1995. Grain sorghum response to sprinkler application methods and system capacity. *Trans. ASAE* 38(6): 1693-1697.

Schneider, A. D., and T. A. Howell. 1997. Methods, amounts, and timing of sprinkler irrigation for winter wheat. *Trans. ASAE* 40(1): 137-142.

Schneider, A. D., and T. A. Howell. 1998. LEPA and spray irrigation of corn: Southern High Plains. *Trans. ASAE* 41(5): 1391-1396.

Schneider, A. D., and T. A. Howell. 2001. Scheduling deficit wheat irrigation with data from an evapotranspiration network. *Trans. ASAE* 44(6): 1617-1623.

Steiner, J. L., T. A. Howell, and A. D. Schneider. 1991. Lysimetric evaluation of daily potential evapotranspiration models for grain sorghum. *Agron. J.* 83:240-247.

TASS, 2006. Texas Agricultural Statistics Service. Quick Stats Texas County Data – Crops. Available at: http://www.nass.usda.gov:8080/QuickStats/CreateCountyIndv.jsp (accessed 20 April 2006).

TWDB, 2001. Surveys of irrigation in Texas, 1958, 1964, 1969, 1974, 1979, 1984, 1989, 1994, and 2000. Texas Water Development Board, Rep. 347. Available at: http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/R347/R347.pdf (accessed 20 April 2006).

Wanjura, D. F., D. R. Upchurch, J. R. Mahan, and J. R. Burke. 2002. Cotton yield and applied water relationships under drip irrigation. *Agric. Water Manage.* 55(3): 217-237.

EVALUATING COTTON YIELD POTENTIAL IN THE OGALLALA AQUIFER REGION

Prasanna Gowda[1]
Allison Esparza[2]
R. Louis Baumhardt[3]
Paul Colaizzi[4]
Terry Howell[5]

ABSTRACT

Renewed interest in cotton production in the Ogallala aquifer region can be tied to development of early maturing varieties, and declining water levels in the Ogallala aquifer. However, the feasibility of growing cotton considering thermal characteristics of the region has not been determined. In this study, the heat unit based county-wide exceedance probability curves for potential cotton yield were developed using a long term temperature dataset (1971-2000) and identified counties that have the potential to grow cotton at 1- and 2-year return periods. Out of 131 counties in the study area, 105 counties have the potential to grow cotton with lint yield more than 500 kg/ha. Evaluation of county-wide potential cotton yield indicate that yield goals based on a 2-year return period may improve the chances of better profits to producers than yield goals with 1-year return period. However, management uncertainties on irrigation efficiencies, fertilizer and pest management, planting and harvesting schedule may require further consideration for estimating potential cotton yield. Nevertheless, these results show that cotton is a suitable alternative crop for most counties in southwest Kansas and all counties in Texas and Oklahoma Panhandles. Also, a significant reduction in annual water withdrawals (about 60.4 million ha-mm) from the Ogallala aquifer for irrigation is possible if producers were to switch 50 percent of their corn acreage to cotton in counties that have yield potential more than 500 kg/ha.

INTRODUCTION

In recent years, cotton (*Gossypium hirsutum* L.) production is slowly expanding to include Central High Plains of the Ogallala aquifer region that includes Texas

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[1] Agricultural Engineer, USDA-ARS-CPRL, Bushland, TX 79012; pgowda@cprl.ars.usda.gov.
[2] amequin81@gmail.com.
[3] Soil Scientist, USDA-ARS-CPRL, Bushland, TX 79012; lbaumhardt@cprl.ars.usda.gov.
[4] Agricultural Engineer, USDA-ARS-CPRL, Bushland, TX 79012; pcolaizzi@cprl.ars.usda.gov.
[5] Agricultural Engineer & Research Leader, USDA-ARS-CPRL, Bushland, TX 79012; tahowell@cprl.ars.usda.gov.

and Oklahoma Panhandles and southwestern counties in Kansas where corn has traditionally been produced (Colaizzi et al., 2004). This renewed interest in cotton production can be associated with the development of early maturing varieties, increasing energy prices, and declining water levels in the Ogallala aquifer (Wheeler et al., 2004). One of the options to potentially reduce the use of groundwater and possibly extend the life of the Ogallala aquifer is to look for drought tolerant, economically viable, alternative crops. Cotton is a perennial tree that has been cultured as an annual crop. Crop water use statistics for Texas High Plains indicate that cotton requires less water (647 mm) than other major crops grown in the region, such as corn (835 mm), sorghum (688 mm) and soybean (681 mm) (Leon and Dusek, 2005). However, temperature, the second most important factor in the development of cotton after water, is a limiting factor in the Central and Northern High Plains of the Ogallala aquifer region. It determines the length of the growing season and has a strong relation with cotton yield (Waddle, 1984).

Cotton needs sunlight and high temperatures for optimum growth with an optimum temperature of 32.2 ^{o}C (Munro, 1987). The amount of heat energy a plant accumulates is usually presented in heat units or growing degree days. A heat unit (HU) is a measure of the amount of heat energy a plant accumulates each day during the growing season, and is calculated from daily maximum and minimum air temperature values as:

$$HU = ({}^{o}C\ \text{maximum} + {}^{o}C\ \text{minimum}) / 2 - T_t\ {}^{o}C \qquad \text{when } HU > 0.0 \qquad [1]$$

This concept of heat units resulted from observations that plants do not grow below a threshold temperature (T_t). The T_t for cotton plant is 15.6 ^{o}C. Crop growth and development of cotton are directly related to accumulated heat units when other environmental factors are not limiting (Peng et al., 1989).

Table 1 presents phenological heat unit requirements for cotton from planting to maturity in the southern Texas High Plains. Cotton requires about 1444 heat units (^{o}C) from planting to harvest to mature a crop (Table 1) (Waddle, 1984). However, in recent years, farmers in the Texas Panhandle have shown that economically viable cotton can be grown with about 1000 heat units (Howell et al., 2004). With 1000 heat units, cotton plant can produce one open boll and 4 more bolls are 85% matured (Wrona et al., 1996). Crop termination through defoliation at this stage of plant development results in a yield loss about 1% of total yield but does not reduce the fiber quality (Wrona et al., 1996).

Table 1. Phenological heat unit requirements for development of cotton crop to maturity in the southern Texas High Plains.

Stage of Development	Plant Age (Days)	Accumulated Heat Units (Base Temp=15.6 ^oC)
Germination-Seedling Establishment	5-15	44-55
Square Initiation	35-50	250-306
First Flower	55-70	528-556
Peak Flower	75-95	506-861
First Open Boll	100-120	1000-1056
50% Open Boll	120-140	1194-1250
80% Maturity	140-170	1278-1361
100% Maturity	150-180	1389-1444

Source: D.R. Krieg, personal communication, 17 Feb. 2006.

Timing of planting and harvesting of cotton has an impact on crop growth, development, and yield. Early planting is important as it helps growers to avoid inclement weather and late-season pests (Silvertooth and Norton, 1999). Generally, cotton is planted when soil temperature reaches 15.6 ^oC or more. Emergence, stand and vigor are adversely affected when soil temperatures fall below 15.6 ^oC. If planted too early when soils are cooler than 12.8 ^oC, a cotton crop may suffer stand loss, seedling disease problems and cold temperature stress, which reduce yield (Sansone et al., 2002). Soil temperature at planting depth is influenced by air temperature due to the proximity of the seed zone to the atmosphere and the thin layer of seed zone soil (Brown, 2000). He demonstrated a linear relation between soil and minimum and maximum air temperature data from the Arizona Meteorological Network (AZMET). Esparza et al. (2006) developed a set of linear regression relationships to estimate daily minimum soil temperature from daily maximum and minimum air temperature in the Ogallala aquifer region. Selection of harvesting date for cotton depends upon first day of freezing in the fall, cotton variety, fall rainfall forecast and/or yield goal.

OBJECTIVES

Due to lower water requirements, availability of early maturing varieties, highly fluctuating energy prices, and depleting groundwater levels, it is believed that cotton is a viable alternative crop to corn in the Southern and Central High Plains of the Ogallala aquifer region. However, there has been no formal study conducted to document the availability and frequency of total heat units during the cropping season and the cotton yield potential in order to determine the physical and financial feasibility of growing cotton. Therefore, the main objectives of this study were to assess (1) thermal feasibility of growing cotton and estimate cotton yield potential; and (2) the potential reduction in Ogallala water withdrawals by growing cotton as an alternative to corn in the region.

MATERIALS AND METHODS

Study Area

This study focuses on the Ogallala aquifer region below 40^{o} N Latitude including all of Southern and Central High Plains and a part of Northern High Plains (Figure 1). There are 131 counties in this region with a total area of about 413,200 km^2. This region is described as being between a semiarid to arid environment in the south and a moist sub-humid environment in the north (McGuire et al., 2003). Annual precipitation in the area ranges from 366 mm in the western part to about 813 mm in the east. The major irrigated crops in the study area include corn, winter wheat, cotton, sorghum, soybean, and peanuts. Although the Southern High Plains are known for cotton production, it was included in the study to estimate potential cotton yield.

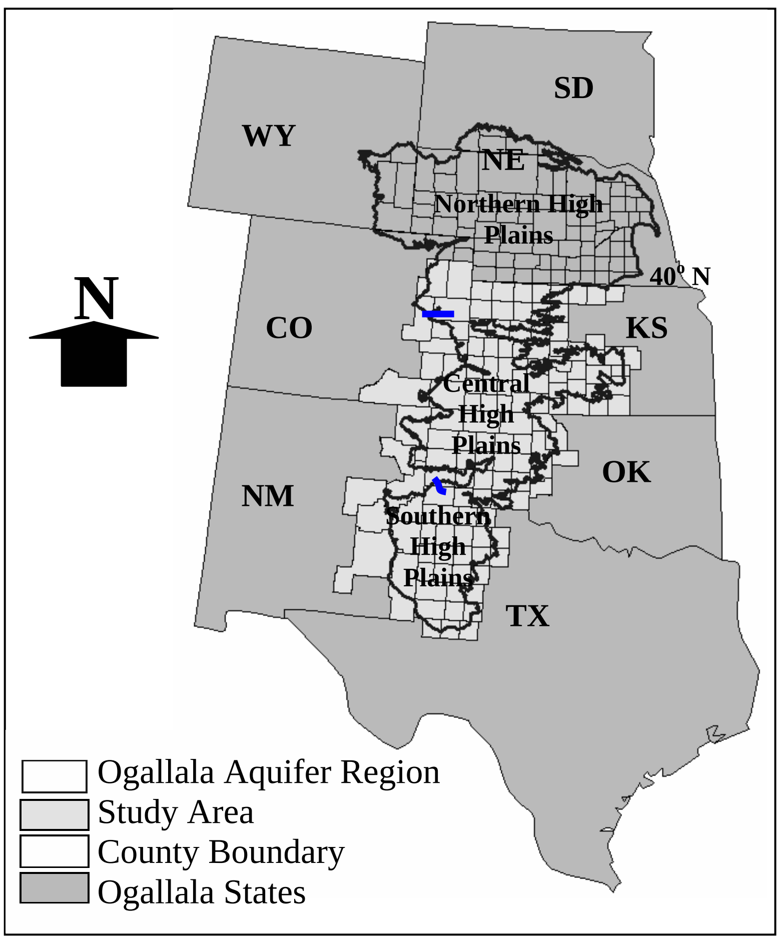


Figure 1. Location of the study area in the central U.S.

Database Development

A long-term climatic data set from the National Climatic Data Center for counties in the Ogallala aquifer region was used in this study. The data set consists of maximum and minimum air temperature data from all weather stations maintained by the National Weather Service (NWS) as well as weather stations maintained by cooperating agencies. Based on the period, availability and continuity of daily observations, a set of weather stations was selected for all counties within the study area. Daily values of maximum and minimum air temperatures were taken from a single station that contained the most complete data in each county. Missing values were supplemented with data from neighboring stations within the same county. For counties with no weather stations, average daily values of maximum and minimum air temperature were interpolated using the data from surrounding counties.

Heat Units and Potential Cotton Yield

For each county, annual heat units accumulated between planting and harvesting dates for cotton was calculated using Eq. [1]. A computer program in FORTRAN was written to automate the county-wide heat unit calculations for the study area. An annually variable planting date for cotton in each county was identified based on the predicted daily minimum soil temperature. Two sets of regression models reported in Esparza et al (2006) for the for Ogallala aquifer region were used to predict daily minimum soil temperature. One regression model is based on maximum air temperature and the other is based on minimum air temperature for each climatic division (NCDC, 2001). Annual cotton planting dates for each county were identified when its estimated daily minimum soil temperature during the planting season was above or equal to a threshold value of 15.6 ^{o}C for both statistical models. The first day of hard freeze or October 15, whichever occurs first, was selected as the harvesting date. This closely mimics observed planting and harvesting time in the Southern High Plains. Although the first frost may not occur during October, producers usually harvest their cotton before third week of October to avoid late season pests and fall precipitation events that affect fiber quality. In the Central and Northern High Plains, frost may occur during the last week of September and may kill the plant if not harvested.

Finally, the county-wide potential cotton yield (*PCY*; kg/ha) was calculated as:

$$PCY = 0 \qquad \text{when } THU < 800\ ^{o}\text{C} \qquad [2]$$

$$PCY = \left[\frac{THU - 800}{41.7}\right] \times 112.5 \qquad \text{when } 800 < THU < 1000\ ^{o}\text{C} \qquad [3]$$

$$PCY = \left[5 + \frac{THU - 1000}{41.7}\right] \times 112.5 \quad \text{when THU >1000 } ^oC \qquad [4]$$

where *THU* is the total heat units accumulated (^{o}C) during the growing season in a given year. The proposed equations are based on three assumptions: (1) *PCY* is equal to zero when *THU* is less than 800, (2) with 1000 heat units accumulated, the cotton plant will have one open boll with 4 more bolls at 85% maturity level and produces approximately 560 kg/ha (500 lb/ac) of cotton lint under irrigated conditions, and (3) with every additional 41.7 (75 ^{o}F) heat units, plant produces one more harvestable boll (Pers. Comm. D. R. Krieg). Equations 2, 3 and 4 were used to estimate *PCY* for counties with *THU* less than 800, in the range of 800-999 and above 999, respectively. With *THU* in the range of 800-999, cotton can be grown; however, it may result in low *PCY* and poor quality lint.

Climatic variability from year to year impact cotton yield as it affects total plant available heat energy during the growing season. Better understanding of climatic variability is important for producers and crop insurance companies to evaluate associated risks. For producers, it helps to set realistic yield goals and plan appropriate management practices. For crop insurance companies, it provides a scientific basis to calculate insurance premiums based on geographic location and yield goals. Therefore, the potential cotton yields were ranked in decreasing order and the exceedance probability (*P*) was calculated as:

$$P = \frac{N}{(n+1)} \qquad [5]$$

where *N* is the rank of the annual estimated value and n is the total number of years (Haan et al., 1994). The exceedance probability for an event of a given magnitude is defined as the probability that an event of equal or greater magnitude will occur in any single year. The return period is calculated as the inverse of the exceedance probability. For example, a rainfall event with an exceedance probability of 0.5 will occur at least once in every two years.

A set of maps was made using Arcview 3.3 (ESRI, 2002) to understand the spatial distribution of heat units and potential cotton yield over the study area. It included county-wide long-term average heat unit and potential yield maps; and potential cotton yield maps with exceedance probabilities of 0.99 (1-yr RT) and 0.5 (2-yr RT). Finally, a county-wide estimate of potential reduction in irrigation withdrawls was made by switching 50 percent of the total corn acreage with cotton in counties that produce 562.5 kg/ha or more (or *THU* of 1000 ^{o}C or more) with a exceedance probability of 50 percent (2-yr return period).

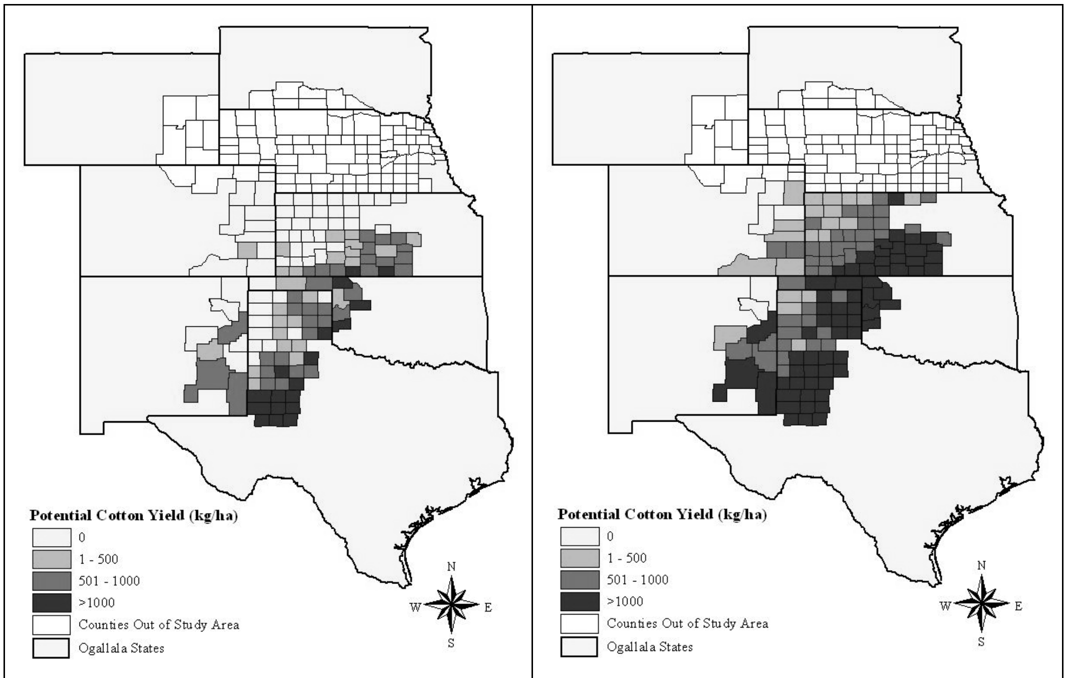
RESULTS AND DISCUSSION

Using long-term (1971-2000) air temperature data, county-wide heat unit accumulation (*THU*) during the growing season and *PCY* for each year were calculated. For most counties, the planting dates were between May 1st and 15th. However, some counties around Lubbock in the Southern High Plains of Texas had planting dates between April 15th and 30th while counties in the east had planting date between May 25 and June 15.

The *THU*s were varied from 582 in Union County, NM to 1724 in Ector County, TX. As expected, the *THUs* were higher for counties located in southern part of Southern High Plains and lower in the Northern High Plains. There were 109 counties including all of the counties except Castro in the Texas High Plains, Oklahoma Panhandle, and southwestern Kansas counties recorded more than 1000 heat units. Only 2 out of 10 counties in Colorado recorded more than 1000 heat units. There were 14 counties in the study area (9 in Kansas) that recorded between 800-999 heat units.

County-wide annual average *PCY* showed a similar trend. The *PCY* varied from zero to 2507 kg/ha for counties with more than 800 heat units. The county-wide average *PCY* values were consistent with average cotton yield reported by Wanjura et al. (2002) for full irrigation treatment yield plots in Lubbock County, Texas.

Figure 2(a-b) illustrates potential cotton yield with 1- and 2-year return periods, respectively. Table 2 presents potential yield-wide distribution of counties under 1- and 2-year return periods. With the 1-year return period, the county-wide annual PCY varied from zero to 1744 kg/ha (Fig. 2a) with an average of 403 kg/ha. About 39 percent of all counties in the study area was estimated to have a PCY more than 500 kg/ha. The PCY varied between 500-1000 kg/ha for 33 counties and exceeded 1000 kg/ha for 18 counties with 15 of them from Texas. Only two counties along southern Kansas border exceeded 1000 kg/ha. However with 2-year return period, the county-wide annual PCY varied from zero to 2488 kg/ha (Fig. 2b) and averaged about 1024 kg/ha. This is about 1.5 times higher than that for 1-year return period indicating that producers may have a better chance to increase their net profit with yield goals that have the return period of 2 years. The annual PCY for 105 out of 131 counties in the study area exceeded 500 kg/ha indicating that cotton can be grown in a major portion of the study area (Table 2) when producers adopt a yield goal with a 2-year return period. The 66 counties with the PCY more than 1000 kg/ha were found along eastern half of the study area with 24 counties located in the south central Kansas (Fig. 2b) where corn is still the major crop of choice under irrigation conditions. This may be partly due to its lower elevation from the mean sea level.



a. 1-year return period **b.** 2-year return period

Figure 2. County-wide potential cotton yield in the study area with two different return periods.

Table 2. Potential yield-wide distribution of the 131 counties in the study area for 1- and 2-year return periods.[1]

Potential Cotton Yield (kg/ha)	Number of Counties	
	1-Year RP (P = 0.99)	2-Year RP (P = 0.5)
0	55	10
< 500	25	16
500-1000	33	39
> 1000	18	66

[1]RP – Return period, P – Exceedance probability

Figure 3 illustrates the county-wide potential water savings if producers were to switch about 50 percent of their total irrigated corn acreage to cotton in counties that had yield of at least 500 kg/ha cotton lint. This converts approximately 325,000 ha presently under irrigated corn (NASS, 2004) to cotton, and provides a potential annual reduction in withdrawal of ground water for irrigation purposes of about 60.4 million ha-mm. About 72 percent of the reduction in water use comes from Kansas counties, because of the relatively large area of irrigated corn and small area of cotton.

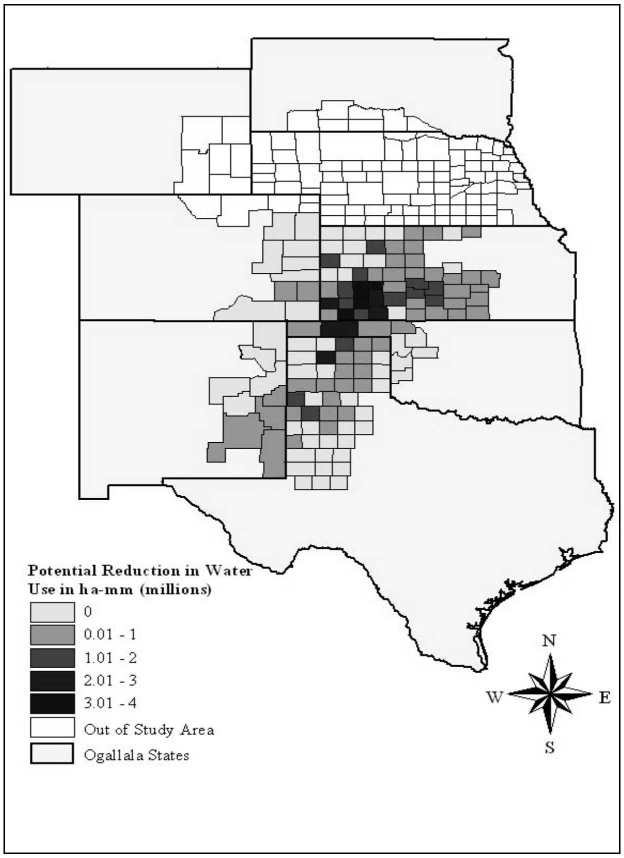


Figure 3. **C**ounty-wide potential reduction in irrigation water use when 50 percent of the irrigated corn acreage was switched to cotton.

CONCLUSIONS

The Ogallala aquifer under Central and Southern High Plains is facing declining water levels and is projected to deplete in about 50 years if the current usage level continues. One of the options to optimize the use of limited water is to look for drought-tolerant and economically viable alternative crops. In this study, we evaluated the feasibility of growing cotton in the Ogallala aquifer region based on potential cotton yield. County-wide potential yield estimates over 30 years (1971-2000) indicate that most counties in Southern and Central High Plains provide suitable climatic conditions to grow cotton. Yield goals based on 2-year return period may give better profits to producers than yield goals with 1-year return period. Management uncertainties, however, on irrigation efficiencies, fertilizer and pest management may require further consideration to estimate potential yield. Nevertheless, these data show that cotton is a suitable alternative crop for the Central High Plains of the Ogallala aquifer region. Significant reduction in water withdrawals from Ogallala for irrigation is possible if producers were to switch 50 percent of their corn acreage to cotton.

REFERENCES

Brown, P. W. 1999. A good planting forecast. [Online] Available at http://ag.arizona.edu/azmet/data/yum00p.pdf (verified 7 April 2006). 1p.

Colaizzi, P.D., S. R. Evett, and T. A. Howell. 2004. Irrigation capacities and methods for cotton in the Northern High Plains. Proceedings of 2004 High Plains Groundwater Resources Conference, Soil and Water Conservation Society of America, 7-9 Dec, Lubbock, TX.

Howell, T. A., S. R. Evett, J. A. Tolk, and A. D. Schneider. 2004. Evapotranspiration of full-, deficit-irrigated and dryland cotton on the northern Texas High Plains. Journal of Irrigation and Drainage Engineering, 130(4):277-285.

Esparza, A. M., P. H. Gowda, R. L. Baumhardt, and C. A. Robinson. 2006. Thermal viability of cotton production in the Ogallala Aquifer Region. Proceedings of the West Texas A&M University 12th Annual Student Research Conference, March 3, 2006, 12p.

ESRI Inc. 2002. Arcview version 3.3. Redland, CA.

Haan, C. T., B. J. Barfield, and J. C. Hayes. 1994. Design hydrology and sedimentology for small catchments. Academic Press, San Diego, CA.

McGuire, V. L., M. R. Johnson, R. L. Schieffer, J. S. Stanton, S. K. Sebree, and I. M. Verstraeten. 2003. Water in storage and approaches to ground-water management, High Plains aquifer, 2000. Circular 1243, U. S. Department of the Interior, U.S. Geological Survey. 51p.

Munro, J.M. 1987. Cotton. 2nd ed. Longman Scientific & Technical, New York, NY.

New, L., and D. Dusek. 2005. Ogallala Aquifer 2004 Annual report – Crop irrigation and production. Texas Cooperative Extension Service, Amarillo, TX, 6p.

National Agriculture Statistics Service (NASS). 2005. Crops state and county data. 1400 Independence Ave. SW Washington, DC 20250.

National Climatic Data Center (NCDC). 2001. Climate divisions. U. S. Department of Commerce, National Oceanic and Atmospheric Administration. Federal Building 151 Patton Avenue, Asheville, NC 28801.

National Climatic Data Center (NCDC). 2002. Cooperative summary of the day TD3200 CD. U. S. Department of Commerce, National Oceanic and Atmospheric Administration. Federal Building 151 Patton Avenue, Asheville, NC 28801.

Peng, S., D. R. Krieg, and S. K. Hicks. 1989. Cotton lint yield to accumulated heat units and soil water supply. Field Crops Research, 19(1989):253-262.

Sansone, C., T. Isakeit, R. Lemon, and B. Warrick. 2002. Texas cotton production: Emphasizing integrated pest management. Texas Cooperative Extension, Texas A&M University System, B-6116, 4-02. 72p.

Silvertooth, J.C. and E.R. Norton. 1999. Planting date effects on soil temperature, crop growth, and yield on upland cotton. Publication No. AZ1170. College of Agriculture, University of Arizona, Tucson, AZ, 12p.

Waddle, B.A. 1984. Crop Growing Practices. *In* R.J. Kohel and C.F. Lewis. (ed.) Cotton. ASA, CSSA and SSSA, Madison, WI. p. 234-264.

Wanjura, D. F., D. R. Upchurch, J. R. Mahan, and J. J. Burke. 2002. Cotton yield and applied water relationships under drip irrigation. Agricultural Water Management, 55:217-237.

Wheeler, E., J. Johnson, E. Segarra, and P. Johnson. 2004. The impacts of Ogallala aquifer characteristics on water use and conservation: The case of Hale County. Proceedings of 2004 High Plains Groundwater Resources Conference, Soil and Water Conservation Society of America, 7-9 Dec, Lubbock, TX.

Wrona, A. F., J. C. Banks, K. Hake, K. Lege, M. Peterson, B. Roberts, C. E. Snipes, and J. Supak. 1996. Achieving a clean finish. Cotton Physiology Today, 7(6):25-31.

A FULLY AUTOMATED CENTER PIVOT USING CROP CANOPY TEMPERATURE; PRELIMINARY RESULTS

R. Troy Peters[1]
Steven R. Evett[2]

ABSTRACT

It has been shown that the temperature-time threshold (TTT) method of automatic irrigation scheduling is a viable alternative to traditional soil water based irrigation scheduling in the Southern High Plains. This method was used to fully automate a center pivot in the panhandle of Texas. An array of 16 IRTCs were mounted on the pivot and connected to a datalogger also mounted on the pivot. A separate array of IRTCs were located in stationary positions in the field and connected to a separate datalogger. Two different spread spectrum (900 MHz) radios were connected to a desktop computer located nearby that queried both dataloggers, got pivot status information, and sent commands to the center pivot control panel. Using scheduled data collection intervals, this computer was able to collect the data, analyze it, determine need for an irrigation event, and issue control commands to completely automate the center pivot. The field under the pivot was divided into pie slices with every other pie slice an automatic treatment. The pie slices in between served as the control and these were scheduled manually to refill the soil water content to field capacity on a weekly basis using neutron probe soil moisture measurements. The preliminary results from this experiment are presented and the statistics showing the differences between the two methods are given.

INTRODUCTION

An automated irrigation scheduling and control system that responds to stress indicators from the crop itself has the potential to lower crop management and labor requirements and to increase yields per unit of irrigation water (Evett et al., 2000). Burke (1993) and Burke and Oliver (1993) showed that plant enzymes operate most efficiently in a narrow temperature range termed the thermal kinetic window. Wanjura et al. (1992, 1995) demonstrated that the use of this window as a canopy temperature threshold could be used as a criterion for simplifying and automating irrigation scheduling. Upchurch et al. (1996) received U.S. patent no. 5,539,637 for an irrigation management system based on this optimal leaf temperature for enzyme activity and a climate dependant time threshold. This was termed the temperature-time-threshold (TTT) method of irrigation

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[1] Extension Irrigation Engineer, Washington State University. 24106 N. Bunn Rd., Prosser, WA 99350; troy_peters@wsu.edu
[2] Soil Scientist, USDA-Agricultural Research Service. P.O. Drawer 10, Bushland, Texas 79012; srevett@cprl.ars.usda.gov

scheduling. With this method, for every minute that the canopy temperature exceeds the threshold temperature one minute is added to the daily total. If this daily total exceeds the time threshold at the end of the day, then an irrigation of a fixed depth is scheduled. Since humidity can limit evaporative cooling, minutes are not accrued if the wet bulb temperature is greater than the threshold temperature minus two degrees Celsius. Evett et al. (1996, 2000) demonstrated in seven years of drip irrigated plots on corn, cotton and soybeans near Bushland, Texas that automatic irrigation using the TTT method was more responsive to plant stress and showed the potential to out-yield manual irrigation scheduling based on a 100% replenishment of crop water use as determined by neutron probe soil water content measurements.

The objectives of this study were to: (1) apply the TTT method of irrigation scheduling to a center pivot irrigation system with an array of infrared thermocouples mounted on the center pivot itself; (2) configure the center pivot to be automatically controlled according to the plant water needs as determined from the TTT method of irrigation scheduling; (3) compare the automatic irrigation scheduling to manual irrigation scheduling based on neutron probe soil water content measurements in the same field.

Diurnal Canopy Temperature Determination

Infrared radiation sensors mounted on self-propelled center pivots or linear move irrigation systems can provide only one-time-of-day canopy temperature measurements at each field location; and these measurements occur at uncertain times of day. The application of the TTT system of irrigation scheduling to specific locations under a center pivot or linear move irrigation system requires a method of determining diurnal canopy temperature dynamics at each location from these one-time-of-day canopy temperature measurements.

Peters and Evett (2004a,b) found that the most direct and simple way to determine how changing environmental conditions over a day affect canopy temperature dynamics is to measure canopy temperature in one stationary reference location. Canopy temperatures in other parts of a field, which may be under different stresses, may be modeled relative to this reference using one-time-of-day temperature measurements from those locations. If pre-dawn canopy temperatures throughout the field (T_e; *e* for early) are assumed to be the same then:

$$T_{rmt} = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \qquad [1]$$

where T_{rmt} (°C) is the calculated canopy temperature at the remote location; T_{ref} (°C) is the canopy temperature from the reference location at the same time interval as T_{rmt} (°C); $T_{rmt,t}$ (°C) is the one-time-of-day canopy temperature measurement at the remote location at any daylight time t; and $T_{ref,t}$ (°C) is the measured reference temperature from the time, t, that the remote temperature measurement was taken.

MATERIALS AND METHODS

The experimental site was a three-tower, 127-m long research center pivot located at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas (35° 11' N, 102° 06' W, 1170 m elev. above MSL). Data were collected during 2004 on soybeans grown on a Pullman fine, mixed, superactive, thermic Torrertic Paleustoll. Only half of the field was used. Soybeans were planted in concentric circles out from the center point (fig. 2). Four different water level treatments were applied radially out from the center point (100%, 66% and 33% of projected irrigation needs, and a dry-land, or no irrigation treatment). The irrigation level was controlled by pressure regulators and nozzle sizes as appropriate. Drops were spaced every other row (1.52 m) and irrigated with low energy precision application (LEPA) drag socks. The furrows were dammed/diked to limit water movement in the furrows. Radially, two replications of each of the irrigation level treatments were applied in a randomized block pattern with the second tower wheel track serving as the block separation line. Along the arc of the irrigated half circle there were three replications each of an automatically controlled (via the TTT method) treatment, and a treatment that was manually scheduled (using soil water deficiency as determined by neutron probe soil moisture content readings). These treatments were applied alternatively to "pie slices" in order to block for any differences in soil types underneath the pivot. The two radial and three arc-wise replications created a total of six replicate

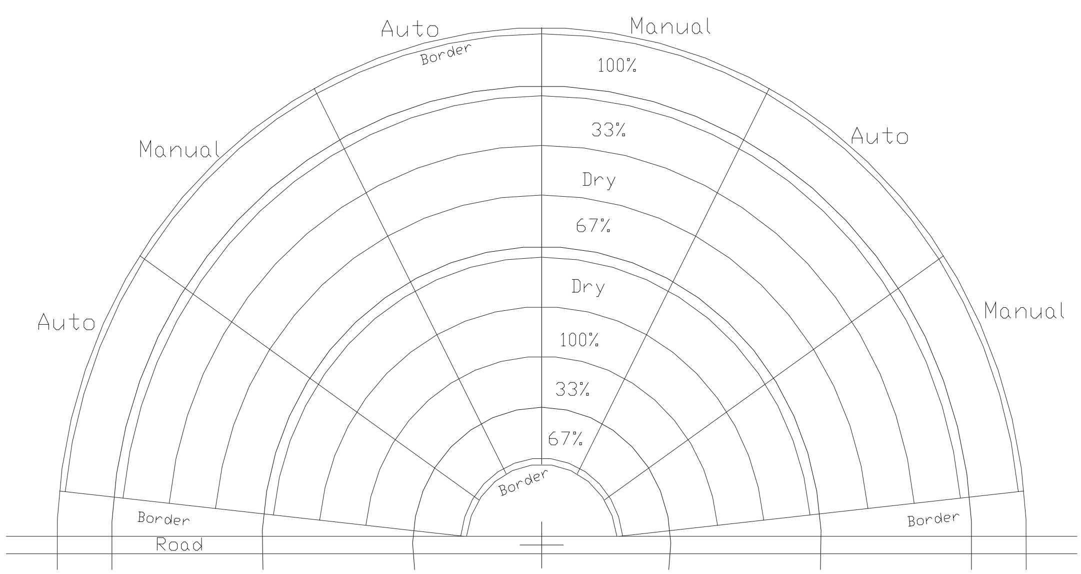

Figure 2. Automatic center pivot irrigation experiment plot plan

plots for each treatment. Two additional rows of soybeans were planted around the outside and inside edges of the pivot to help minimize border effects. Agronomic practices common in the region for high yields were applied.

The pivot movement and positioning were controlled remotely by a computer, located in a nearby building, which communicated through two different 900-MHz radios (fig. 3). One radio was part of a center pivot remote control system ("Base Station") produced by Valmont Industries[3]. This radio communicated with the pivot through a second radio mounted at the pivot center point, thus allowing status checks and control commands to be sent and received at the pivot control panel. The second system consisted of a Campbell Scientific RF400 radio that communicated to similar radios connected to a datalogger mounted on the pivot and a separate datalogger in the field.

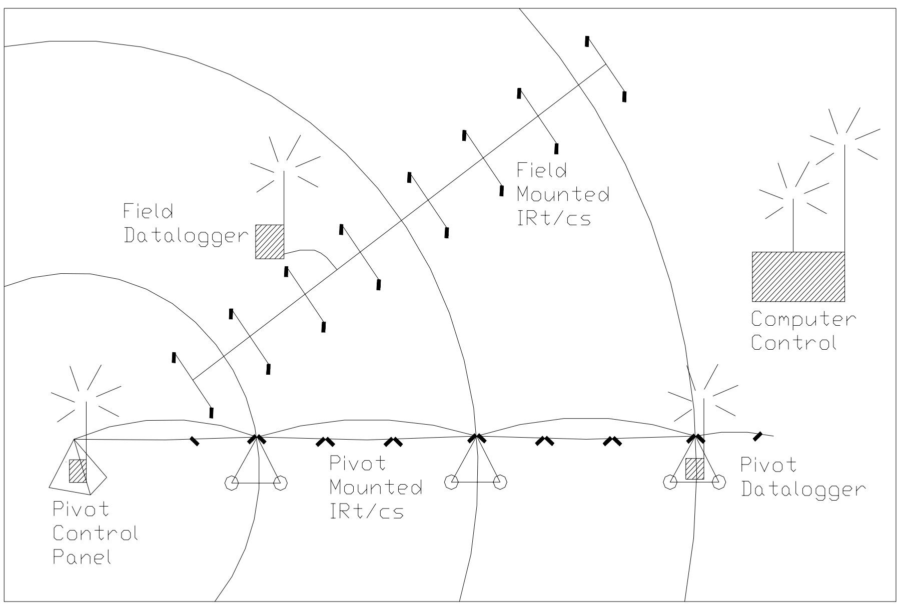

Figure 3. Automatic center pivot control set-up.

The center-pivot-mounted datalogger collected data from 16 infrared thermocouple thermometers (IRTC) that were attached to the trusses of the pivot (fig. 3). They were mounted on the leading side of the pivot and the pivot was only allowed to irrigate in one direction so that the sensors would not view wet canopy. The IRTCs were oriented so that they pointed parallel to the center pivot arm (perpendicular to crop rows) towards a spot in the middle of each concentric irrigation treatment plot. In order to minimize sensor angle related effects, two

[3] Mention of trade names or commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture

IRTCs were aimed at approximately the same spot from either side of each plot. The average of these two readings for each plot was used. Wanjura et. al. (1995) reported that canopy temperatures differed less than 0.5° C when measured by either one sensor in the nadir position, or two sensors pointed at the row from opposite directions. The IRTCS were connected to a multiplexer (Campbell Scientific AM25T) at the second tower, which in turn was connected to a datalogger (Campbell Scientific CR10X) placed at the third and last tower. The IRTCs were sensed for canopy temperature on 10 second intervals; and the one minute averages were logged.

Sixteen IRTCs (Exergen model IRt/c.2-T-80) were mounted in stationary locations in the field and connected to a separate datalogger (fig. 3). Each IRTC was mounted in the nadir position over the crop row close enough to the canopy so that soil was not included in the field-of-view. These IRTCs were adjusted up with the changing height of the canopy. One IRTC was mounted in each irrigation level of both the automatic and manual treatments. These IRTCs were similarly connected through a multiplexer (Campbell Scientific AM25T) and to a datalogger (Campbell Scientific CR21X). The datalogger logged the five minute averages of each of the IRTC readings collected on 10 second intervals.

Each IRTC was separately calibrated using a black body (Omega Black Point, model BB701) before the season began. A second order polynomial was fitted to the results of the calibration and each IRTC was individually corrected by the data analysis software running on the control computer in the nearby building.

During an automatic irrigation event the pivot stopped at the edge of the treatment, paused 10 minutes to drain, and then ran dry over the manual irrigation treatment. It would then pressure up again for the next automatic irrigation treatment and continued on in this fashion until all of the automatic irrigation segments were irrigated. An application depth of 20 mm was applied at each automatic irrigation event. This was equivalent to the maximum, two-day evapotranspiration rate for the region during the hot, windy summer months. After irrigating the last automatic plot the pivot continued on around dry to its starting point. During a manual irrigation event the pivot performed similarly except it would irrigate only the manual irrigation treatments at a manually set application depth required to replenish soil water content to field capacity (0.33 m^3 m^{-3}), thus preventing crop stress for the 100% treatments. The soil water deficit was determined by weekly neutron probe readings in the 100% manual irrigation treatments. The neutron probe was field calibrated as in Evett and Steiner (1995) and was read at 20-cm depth increments. A depth control stand (Evett et al., 2003) was used to improve accuracy in the near-surface (10-cm depth) reading. In order to both manually and automatically control the same pivot, automatic irrigations were only allowed on even days of year, and manual irrigations were only allowed on odd days of year.

The central control computer was programmed to call the pivot-mounted datalogger and the pivot control panel every minute to retrieve status reports. Software was written in Visual Basic that reviewed the status reports every minute to determine whether the pivot had crossed a plot boundary. If it had, new instructions were sent to the pivot depending on its location and the program (automatic or manual) that was running at the time. In this way the complex motion of the center pivot was controlled.

The field datalogger was polled only once a day soon after midnight. At this time the previous day's data were analyzed to determine the next day's strategy. If the pivot did not move during the previous day, the temperature curve collected by the pivot-mounted IRTCs was used to determine whether irrigation was required. If the pivot *did* move during the previous day then a subroutine was called that scaled one time-of-day temperature measurements and made decisions based on the results. The two canopy temperature measurements from the field-mounted IRTCs in the 100%, automatic treatments were averaged together and used as the reference curve for scaling the one time-of-day measurement into a diurnal curve (equation 1).

To establish the plots, the plots were uniformly irrigated until the soil between the rows was not visible when viewed at a 45° angle from the pivot IRTCs. At the end of the season the dry yield was determined by harvesting a 3.48 m^2 sample near the center of each plot. The total dry biomass was measured, as well as the dry yield, Y (kg m^{-2}), and average bean weight. The total water use, W_U (m), was determined by subtracting the soil profile water content (m) determined at the first measurement date from the water content determined after harvest, and adding the total amount of irrigation, I (m), and rainfall (m) for that time period. Water use efficiency (*WUE*) was calculated as:

$$WUE = \frac{Y}{W_U} \qquad [2]$$

and irrigation water use efficiency (*IWUE*) was calculated as:

$$IWUE = \frac{Y - Y_D}{I} \qquad [3]$$

where Y_D was mean yield (kg m^{-2}) in the dryland plots. Both WUE and IWUE are given in units of kg/m^3.

RESULTS AND DISCUSSION

Exergen IRTCs have a capacitor built into the sensor to help to minimize the effects of ambient electromagnetic noise on the sensor's readings. This capacitance interacts with the Campbell Scientific CR10X datalogger to give readings that are slightly incorrect. The pivot-mounted IRTCs were wired into a CR10X. This is not an issue with the Campbell Scientific CR21X that was used for the stationary field measurements. It was discovered that the pivot-mounted, narrow field-of-view sensors were particularly sensitive to the sensor body temperature and gave errant readings when the sensor bodies were at elevated or cooler temperatures. Because the sensors were calibrated independently in the laboratory before mounting them on the pivot, and because the readings were reasonable, this error was not caught until after the season was effectively over. This resulted in pivot IRTC temperatures that were highly variable and that gave answers that were generally three to five degrees Celsius low.

The pivot IRTC measured temperatures were compared to the field IRTC data from times when the pivot was located in approximately the same location (Figure 4). It was found that the pivot mounted IRTCs varied linearly with the more correct field IRTCs. Regression was used to obtain the equation:

$$T_{corrected} = 0.7641 \cdot T_{pivot} + 9.1713 \quad [4]$$

This equation can be used to obtain a corrected ($T_{corrected}$) canopy temperature using the pivot temperatures (T_{pivot}) (both in ˚C) with an r^2 value of 0.9731.

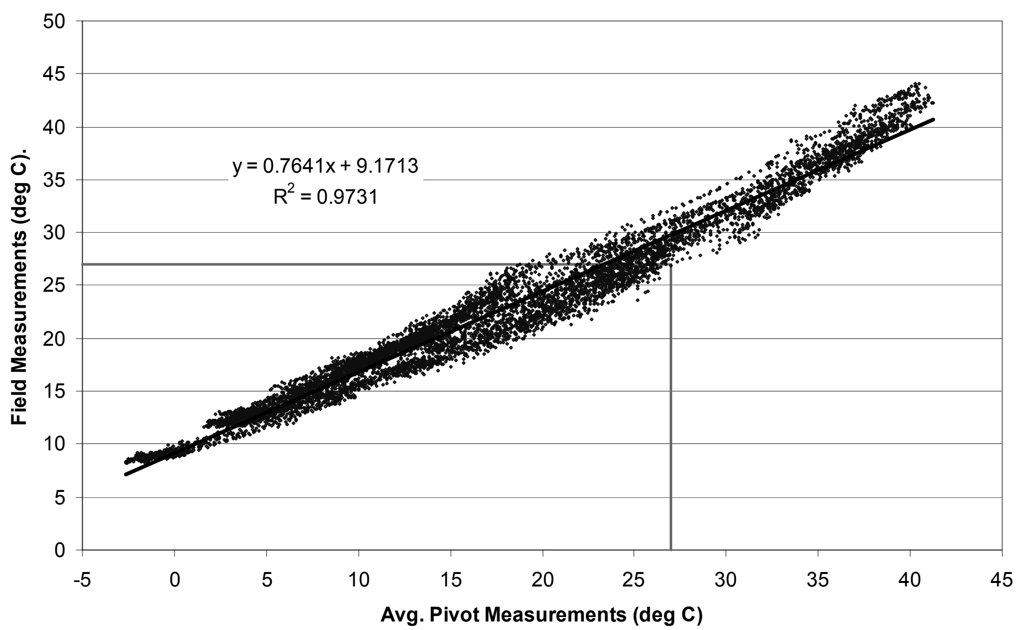

Figure 4. Regression of measured canopy temperatures on the pivot with those measured in stationary location near where the pivot was located.

To evaluate the effect that this error had on the irrigation experiment, the corrected temperatures were run back through a specifically written computer program. The irrigation decisions of what should have happened if the sensors were reading correctly were compared against what was actually done. The results showed that in five different instances throughout the season automatic irrigations should have run but didn't because the temperatures were reported low. The temperature threshold was effectively set at 30 ˚C instead of the 27 ˚C for soybeans that is specified by theory. When tested, there was no difference in the irrigation decisions made by the uncorrected data with at 27 ˚C temperature threshold and the corrected temperatures with a 30 ˚C temperature threshold.

The yield data from 2004 were analyzed using SAS (SAS Institute, Inc., Cary, NC) with a procedure for mixed models (Proc Mixed) with the Tukey-Kramer method for adjusting for multiplicity (Table 1). The manual irrigation treatment yielded significantly more than the automatic irrigation treatment ($Pr > |t| = 0.035$) with an average difference of 0.025 kg/m^2 (Table 1). We believe that this was mainly due to the sensor issue, which was equivalent to the temperature threshold being set three degrees Celsius greater than it should have been. Although not significantly different, the manual treatments also showed numerically larger WUE and IWUE. There were no significant differences between the automatic and the manual treatments for any variable (yield, bean mass, etc.) within an irrigation level, with the exception of yield at the 67% irrigation level.

Table 1. 2004 response variables for the treatment (automatic vs. manual), the irrigation level (100%, 66%, 33%, and dry), and the cross between the two. Numbers in a column followed by the same letter are not significantly different at the 0.05 probability level.

		Dry Yield (kg/m^2)	Avg Bean Weight (mg/bean)	Biomass (g)	Wtr Use Efficiency (kg/m^3)	Irrig Wtr Use Efficiency (kg/m^3)	Total Water Use (mm)
Treatment	Manual	0.272 A	133 A	1222 A	1.30 A	0.77 A	218 B
	Auto	0.289 A	130 A	1306 A	1.18 A	0.73 A	254 A
Irrigation Level (%)	100%	0.383 A	148 A	1630 A	1.10 A	0.77 A	351 A
	67%	0.321 B	140 A	1380 B	1.18 A	0.80 A	273 B
	33%	0.239 C	125 B	1112 C	1.25 A	0.69 A	193 C
	Dry	0.178 D	114 B	934 D	1.43 A		127 D
Treatment * Irrigation Level	Manual 100%	0.374 A	150 A	1556 AB	1.16 B	0.84 A	323 B
	Auto 100%	0.391 A	145 A	1705 A	1.03 B	0.71 A	379 A
	Manual 67%	0.307 B	143 A	1310 CD	1.21 B	0.82 A	254 C
	Auto 67%	0.335 B	138 AB	1451 BC	1.15 B	0.78 A	292 B
	Manual 33%	0.229 C	126 BC	1064 EF	1.28 AB	0.66 A	180 D
	Auto 33%	0.249 C	124 CD	1159 DE	1.21 AB	0.72 A	207 D
	Manual Dry	0.177 D	113 D	958 F	1.54 A		116 E
	Auto Dry	0.180 D	114 CD	909 F	1.33 AB		137 E

CONCLUSION

A center pivot was configured to automatically irrigate based on crop stress signals sensed by infrared thermocouples mounted on the center pivot. These automatic treatments were compared with a manually scheduled treatment in 2004. There was an interaction of the sensors with the datalogger; and a problem with the sensor readings being highly sensitive to the sensor body temperature was found. This caused incorrect canopy temperatures to be recorded by the pivot-mounted IRTCs. This resulted in the equivalent of the threshold temperature being set at 30˚ C instead of the prescribed 27˚ C. Therefore, the automatic irrigations ran less often than they should have. Because of this, the manual treatment's yields were significantly higher than the automatic treatments. There were no significant differences in water use efficiency. We believe that the costs and simplicity of methods presented here may become attractive to producers when available in a turn-key commercial package. This is especially true since the methods presented have the potential to simplify management and reduce labor costs while maintaining or increasing yields compared with intensively and scientifically managed manual irrigation scheduling.

REFERENCES

Burke, J.J. 1993. Thermal kinetic windows of plant enzymes. In *Biotechnology for Aridland Plants, Proc. International Symp. IC[2] Institute.* Mabry, T.J., Nguyen, H.T., Dixon, R.A., Bonness, M.S. (eds.) The University of Texas, Austin. (pp. 73-82.)

Burke, J.J., and M.J. Oliver. 1993. Optimal thermal environments for plant metabolic processes (Cucumis sativus L.): Light-harvesting chlorophyll a/b pigment-protein complex of photosystem II and seedling establishment in cucumber. *Plant Phys.* 102(1):295-302

Evans, R.G. 2000. Controls for Precision Irrigation with Self-Propelled Systems. In *Proc. of the 4th Decennial National Irrigation Symposium*. Robert G. Evans, Brian L. Benham, and Todd P. Trooien (eds.) November 14-16, Phoenix, AZ.

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 1996. Canopy temperature based automatic irrigation control. In *Proc. International Conf. Evapotranspiration and Irrig. Scheduling*. C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.). November 3-6, 1996, San Antonio, TX. (pp. 207-213)

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 2000. Automatic drip irrigation of corn and soybean. In *Proc. of the 4th*

Decennial National Irrigation Symp. Robert G. Evans, Brian L. Benham, and Todd P. Trooien (eds.). November 14-16, Phoenix, AZ. (pp. 401-408)

Evett, S.R., and R.J. Lascano. 1993. ENWATBAL.BAS: A mechanistic evapotranspiration model written in compiled BASIC. *Agron. J.* 85(3):763-772.

Peters, R.T., and S.R. Evett. 2005. Using low-cost GPS receivers for determining field position of mechanized irrigation systems. *App. Eng. in Ag.* 21(5): 841−845

Peters, R.T., and S.R. Evett. 2004(a). Modeling diurnal canopy temperature dynamics using one time-of-day measurements and a reference temperature curve. *Agron. J.* 96:1553-1561

Peters, R.T., and S.R. Evett. 2004(b). Comparison of scaled canopy temperatures with measured results under center pivot irrigation. In: Proceedings of the 25th Annual International Irrigation Show of the Irrigation Association. Nov. 14-16, 2004. Tampa, FL. CDROM

Upchurch, D.R., Wanjura, D.F., Burke, J.J. and Mahan, J.R. 1996. Biologically-identified optimal temperature interactive console (BIOTIC) for managing irrigation. U.S. Patent No. 5539637.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1992. Automated irrigation based on threshold canopy temperature. *Trans. ASAE* 35(1):153-159.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1995. Control of irrigation scheduling using temperature-time thresholds. *Trans. ASAE* 38(2):403-409.

AGRICULTURAL WATER LEASING — A SUPPLEMENTAL WATER SUPPLY STRATEGY FOR A GROWING CITY

Cortney C. Brand[1]
Kevin D. Lusk[2]

ABSTRACT

Colorado, including much of the western United States, experienced a severe drought that extended from 2000 into 2005. In 2002, stream flows in Colorado were measured at their lowest discharge rates in more than 100 years. Due to the extended and severe nature of this recent drought coupled with increasing demands, Colorado Springs Utilities (Springs Utilities) implemented an aggressive drought response program that included rigorous watering restrictions and other supply management strategies. Although the program saved an estimated 62,000 acre feet (AF) over four years, water storage levels still fell to a low of 42 percent of storage capacity in early 2003, and the organization experienced significant revenue shortfalls. In order to recover from extended drought and to augment water storage, Springs Utilities participated in a one-time agricultural water lease with a mutual ditch company on the lower Arkansas River. The agricultural water lease was conducted through the State's Substitute Water Supply Plan program and involved the temporary leasing of individual shares of the mutual ditch company. The net yield of Colorado Springs' portion of the lease was 4,337 AF and, combined with other water leases, restored water storage levels to nearly pre-drought levels.

INTRODUCTION

Background

Springs Utilities, an enterprise of the City of Colorado Springs, provides water, wastewater, natural gas and electric services to a community of nearly 500,000. Springs Utilities' water demands average nearly 85,000 acre-feet per year (AF/yr), and usage varies seasonally from an average of 45 million gallons per day (MGD) in the winter to a peak of more than 160 MGD in the summer. Due to a growth rate three times the national average, the City's water demands are projected to increase to as much as 180,000 AF/yr by 2045. The City's water supply is primarily surface water (approximately 97 percent) obtained from the Arkansas, Colorado, and South Platte River basins (Figure 1).

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[1]Senior Project Engineer, Colorado Springs Utilities, 215 Nichols Blvd., Colorado Springs, CO 80907; cbrand@csu.org.
[2]Principal Engineer, Colorado Springs Utilities; klusk@csu.org.

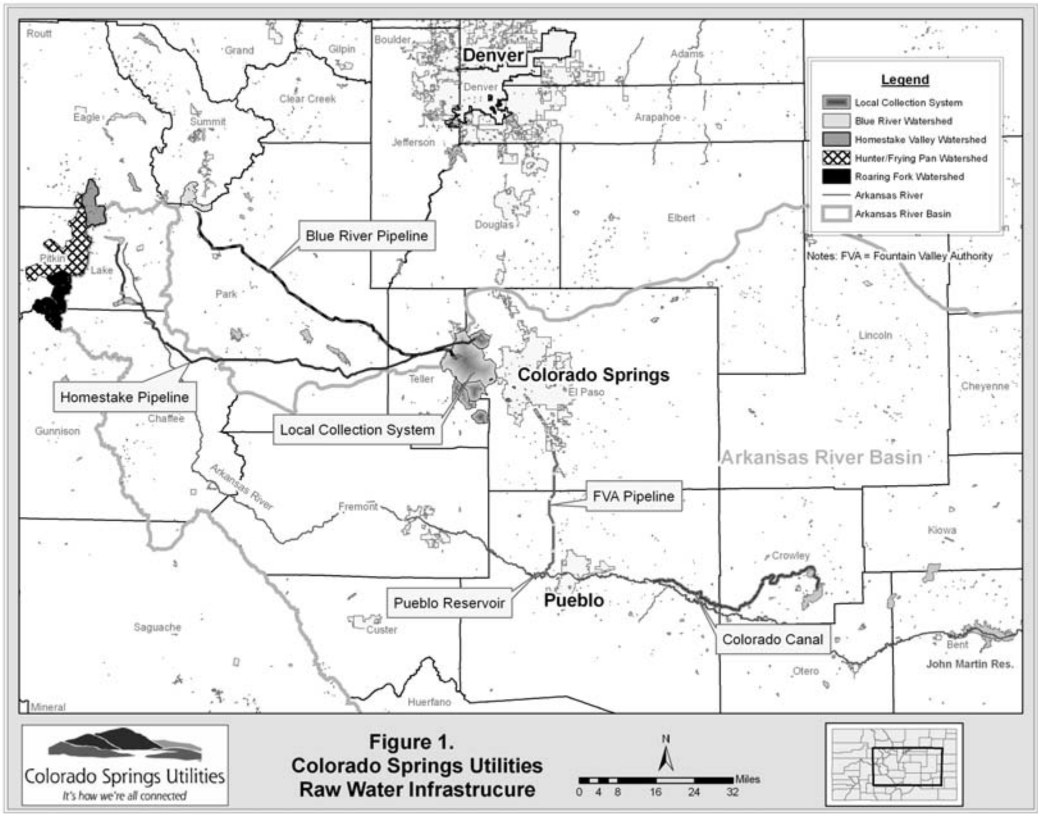

Figure 1. Colorado Springs Utilities Raw Water System

Colorado Springs possesses substantial water storage capacity (244,000 AF) and some supplemental water sources, including alluvial and bedrock groundwater. However, due to its reliance on surface water and limited groundwater resources, the City's water supply system is susceptible to extended and severe droughts.

Physical Setting

The City of Colorado Springs is located at the base of Pikes Peak along the Front Range of Colorado, approximately 70 miles south of Denver (Figure 1). Elevation varies by more than 1,000 feet within the City, ranging from 6,000 to more than 7,000 feet above mean sea level (amsl); and the climate is semi-arid with annual precipitation averaging 15 inches. Local water supplies are insufficient to meet the needs of the City, so Colorado Springs has developed an extensive network of reservoirs, diversions, tunnels, pipelines and canals that collect water from three major river basins and deliver it from as far away as 200 miles.

Even though Colorado Springs is situated in the Arkansas River basin and a large portion of its water supply originates from, or is conveyed through, the Arkansas River, the City is located more than 40 miles from the river at its closest point. Thus, the City relies upon several major pipelines to deliver its water (Figure 1). The Arkansas River can be separated into two reaches: (1) Upper Basin –

headwaters near Leadville to Pueblo Reservoir near Pueblo, and (2) Lower Basin – Pueblo Reservoir to the Kansas state line. The Upper Basin is mountainous, and water is used for recreation, municipal uses, industry and some agriculture. The Lower Basin, in contrast, is relatively flat and water is primarily used for agriculture and limited municipal uses. There are approximately 86,000 irrigated acres in the Upper Basin compared to almost 300,000 in the Lower Basin.

Water Rights Background

Two characteristics of Colorado water law are central to a discussion of agricultural water leasing: (1) over-appropriation and (2) maintenance of historical diversion and return flow patterns. In most of Colorado, water is scarce and the river systems are over-appropriated, meaning that there are more water rights than there is water to satisfy those rights. As a result, water rights are strictly administered and accounted for under the doctrine of prior appropriation, i.e. “first in time, first in right.” Water year 2002 provides a salient example of the over-appropriated nature of Colorado’s rivers. Representative “call” dates on the Colorado, Arkansas and South Platte rivers during the summer of 2002 were 1902, 1869 and 1863, respectively. Thus, only the most senior water right holders were able to divert during this time, and entities such as Colorado Springs were forced to draw down reservoir storage to meet demands.

The other characteristic of Colorado water law that is most relevant to agricultural water leasing, is the maintenance of historical diversion and return flow patterns. The purpose of maintaining these patterns is to prevent injury to downstream water right holders. Because of the over-appropriated nature of the river system, downstream water rights holders often are diverting the return flows of upstream users. In this way, the water is used and reused multiple times before it reaches the State line. For example, if water is temporarily leased from an irrigation ditch company, the water must still be diverted at the company’s headgate and conveyed through its canal system; and only the portion of the water that was historically consumed can be transferred. This process assures that the water is diverted at the same place and time as has occurred historically, that historical canal seepage patterns are maintained and that there is no reduction in historical return flows to the river, which downstream diverters depend upon.

Thus, the operation of agricultural water leases in Colorado requires a considerable amount of engineering, hydrologic analysis and accounting to prevent injury to other water right owners. This is further compounded by the use of exchanges to “move” the leased water to a location where it can be delivered to the lessee. Exchanges in Colorado are a non-structural means of trading water within a river system by “borrowing” water from the river at a location upstream and “repaying” the river at a different location downstream. These exchanges are administered under the priority system similar to other water rights.

Regulatory Framework

The Colorado Office of the State Engineer (State Engineer) administers, and has the authority to approve, Substitute Water Supply Plans (SWSPs) pursuant to CRS 37-92-308. In general, SWSPs provide water users with a mechanism to replace out-of-priority depletions on an interim basis. This allows temporary changes of water use and, in the case of permanent transfers, the protection of other water rights during litigation involving change of use cases and augmentation plans. Changes of water use, temporary or permanent, typically have to go through the Water Court adjudication process. However, the 2002 and 2003 General Assemblies granted the State Engineer authority to approve SWSPs considering that there are certain circumstances under which the time associated with the Water Court adjudication process is problematic for some water users.

The subject agricultural water lease was accomplished through the SWSP program. The State Engineer, through the SWSP program, approved the change of use of agricultural water rights to municipal use on a temporary basis with conditions for dry-up verification, analysis of historical consumptive use and demonstration of no injury to downstream water rights holders. The current statute limits these sorts of agreements to be conducted three out of ten years.

AGRICULTURAL WATER LEASE

In fall 2004, Colorado Springs' water storage levels were at 59 percent of capacity and the forecast was for below average snowpack conditions in Colorado Springs' watersheds. Even with average snowpack, Springs Utilities water supply planners predicted that system yields would fall short and that water storage would be further depleted in 2005. As a result, Springs Utilities decided to pursue supplemental supply strategies to stabilize water storage levels and to avoid the additional revenue shortfall from more aggressive watering restrictions.

One of the supplemental water supply strategies pursued by Springs Utilities involved the temporary leasing of agricultural water rights in the lower Arkansas River Valley. In 2003, the City of Aurora (Aurora), Colorado, had previously developed agreements with a portion of the shareholders of the Rocky Ford High Line Canal Company (High Line) to lease their shares for up to three years ending in November 2005. The High Line is a Colorado mutual ditch company with relatively senior direct flow rights on the Arkansas River, which are diverted approximately 35 miles downstream of the City of Pueblo and used to irrigate nearly 22,500 acres along an 87-mile long canal system (Figure 2). The High Line consists of 2,250 shares, and each share serves 10 acres.

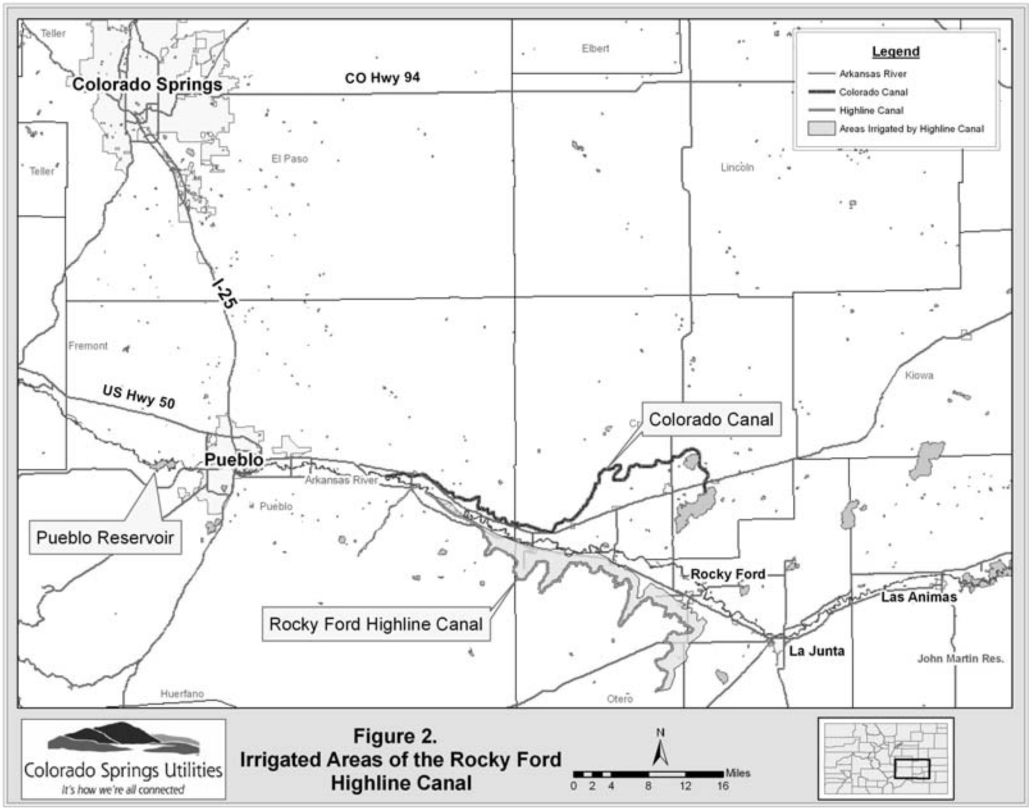

Figure 2. Location of the Rocky Ford High Line Canal System

Aurora leased approximately 37 percent of the High Line shares (total of 833.8 shares) by developing separate agreements with numerous shareholders. Depending upon stream flow conditions, it was anticipated that these shares would produce between 14,000 and 15,000 AF of water in an average year. The consumptive use credit varied on a monthly basis from approximately 30 percent up to 43 percent of the water determined to be available in-priority to the leased shares. Aurora took delivery of leased water in 2004, and had the option to do so again in 2005. The lease was exercised again in 2005, and Colorado Springs developed an agreement with Aurora to sublease the yield from approximately half of the High Line shares (up to 417 shares) that it leased.

Structure of Lease Agreements

The primary lease agreement between Aurora and the High Line Canal Company allocated responsibilities and risks to the lessee and the High Line shareholders. Colorado Springs assumed additional incremental risk in its sublease agreement with Aurora. The following describe some of the main components of the primary lease and sublease agreements:

- The lease price was determined on an annual, per share basis. In this way, the shareholders received a guaranteed price; whereas, the lessee's yield was not guaranteed and depended upon the per share yield from the High Line's in-priority diversions.

- High Line shareholders were to receive a non-refundable minimum payment of $100 per share regardless of whether or not the lease was exercised in the given year.
- Recognizing that historically irrigated lands that are idle for an extended period may experience a reduction in productivity, the lessees agreed to pay $1,000 per share for each year the land is out of production pursuant to the lease, not to exceed $2,000 per share.
- Shareholders are obligated to make annual Ditch Company Assessment payments. Therefore, the lessees agreed to pay the shareholders $100 per share for High Line stock assessments. The shareholders were responsible for any additional assessment costs.
- High Line shareholders were responsible for paying any taxes, property or otherwise, associated with the fallowed land or company stock.
- High Line shareholders, at their sole cost, were responsible for weed control and mitigation of blowing dust and erosion on the fallowed lands.
- Colorado Springs agreed to reimburse Aurora for a *pro rata* portion of its costs to develop the leasing program.
- Colorado Springs was responsible for providing a *pro rata* portion of the return flow obligations assigned in the 2005 SWSP, which amounted to approximately 900 AF of water.
- For the administration of the agreement and for use of the subleased water, Colorado Springs agreed to compensate Aurora with water. If the total historical consumptive use yield of the sublease agreement was less than 6,000 AF, Colorado Springs would deliver 600 AF to Aurora. If the actual yield exceeded 6,000 AF, then Colorado Springs would deliver to Aurora up to 1,200 AF.

Yield from Lease

The gross yield to Colorado Springs from its sublease with Aurora was 5,837 AF. After deducting the water provided to Aurora as compensation for administration of the lease and the water forfeited for return flow obligations, the net yield of the lease was approximately 4,337 AF, or about 74 percent of the gross yield. Colorado Springs' total costs amounted to approximately $2.7 million. Therefore, based on the net yield, the cost of the leased water worked out to be approximately $623 per AF.

Although the cost of the leased water was relatively high, the program benefited both the lessees (Aurora and Colorado Springs) and the High Line shareholders, and established further precedent for implementing temporary agricultural water leases in the lower Arkansas River. Colorado Springs and Aurora received water needed to firm-up storage and the High Line shareholders received money needed to cover liabilities. In addition, significant improvements were made to the High Line canal system to implement the lease, which benefited all shareholders.

FUTURE WATER LEASE PLANNING

Springs Utilities does not anticipate leasing water in 2006, however, the need could arise again in the future. Potential events that could trigger the need to lease water again include (1) continuation and intensification of the current drought cycle, (2) curtailment, partial or full, of Colorado River imports as a result of a Lower Basin "call", and/or (3) significant delay of current water supply and delivery system development activities. Realizing that each of these events is possible, Springs Utilities Water Supply staff is conducting planning around future agricultural water leasing.

Water Clearinghouse Concept

Springs Utilities has investigated the concept of developing a "water clearinghouse" in the lower Arkansas River Valley. The concept generally consists of establishing a market and an exchange to facilitate agricultural water lease and purchase transactions. To be successful, the concept might involve the consolidation of separate ditch company shares, a large-scale and formalized rotational fallowing program, and the establishment of a market-based exchange to carry out auctions and to facilitate transactions between buyers and sellers.

The current economic conditions in the lower Arkansas River Valley and in some other agricultural areas of Colorado are becoming more conducive to water trading. Many farmers are ready to sell their water and monetize their asset due to prolonged low returns on investment and increasingly global competition. At the same time, public water suppliers are looking to purchase additional supplies, temporarily or permanently, to firm-up existing supplies and/or to meet future demands. A common, consistent and relatively transparent process for conducting agricultural water lease transactions could be mutually beneficial to farmers and public water suppliers alike, and would promote the efficient and economic utilization of the State's valuable water resources.

DEFICIT IRRIGATION OF ALFALFA AS A STRATEGY FOR PROVIDING WATER FOR NONAGRICULTURAL USES

Blaine Hanson[1]
Dan Putnam[2]
Rick Snyder[3]

ABSTRACT

Alfalfa is California's single largest agricultural water user due to its large acreage and long growing season, using 4 to 5.5 million acre feet of water each year. Because of this water use, the California Department of Water Resources is interested in deficit irrigation of alfalfa for providing water for transfer elsewhere. One strategy is to terminate irrigation during July and August when alfalfa yields are relatively small and use the "saved" water for nonagricultural uses. The amount of transferable water would be the difference in the evapotranspiration (ET_c) of a fully-irrigated field and that of a deficit-irrigated field; however, no information exists on the potential ET_c differences.

Evapotranspiration was determined in a commercial field using the eddy covariance and surface renewal energy balance methods in a fully irrigated part of the field, and the surface renewal method in the deficit irrigated part of the field. In addition, alfalfa yield, applied water, canopy coverage and plant height measurements were made in both parts of the field.

Deficit irrigation greatly reduce alfalfa yield in 2003, 2004, and 2005. Yield reductions due to deficit irrigation generally ranged from 41 to 88% of the fully-irrigated treatments. Cumulative ET_c in 2005 was 48.1 inches for the fully-irrigated treatment. Deficit irrigation (no irrigation) started on July 25. Cumulative ET_c between July 25 and December 6 (end of measurement period) was 20.8 inches for the fully irrigated treatment and 11.4 inches for the deficit irrigated treatment for a difference of 9.4 inches.

INTRODUCTION

Water transfers from the water-rich agricultural areas of northern California are

[1] Extension Irrigation and Drainage Specialist, Dept. of Land, Air and Water Resources, University of California, Davis, CA; brhanson@ucdavis.edu
[2] Extension Forage Specialist, Dept. of Plant and Environmental Sciences, University of California. Davis, CA; dhputnam@ucdavis.edu.
[3] Extension Biometeorology Specialist, Dept. of Land, Air and Water Resources, University of California, Davis, CA; rlsnyder@ucdavis.edu

being used by the California Department of Water Resources to supply water to areas with limited water supplies. The strategy is to fallow land and then transfer an amount of water equal to the seasonal evapotranspiration (ET_c) of the crop that would normally be grown in the fallowed fields. It is assumed that no ET_c occurs in the fallow fields.

Alfalfa is California's single largest water user due to the amount grown, typically about one million acres, and its long growing season. Seasonal alfalfa water use generally ranges from 4 to 5.5 million acre-feet per year. Because of this large water use, the Department of Water Resources is interested in transferring water from alfalfa production to other uses during periods of water shortage. A possible strategy is to deficit irrigate the flood-irrigated alfalfa fields during July and August, a period of time during which both alfalfa yield and water use efficiency (ratio of yield to ET_c) are relatively small. Deficit irrigation consists of terminating flood irrigations during those months.

Unlike a fallow field, deficit irrigated alfalfa can continue to transpire. The difference in ET_c between fully-irrigated and deficit-irrigated alfalfa is unknown because of this transpiration. Also unknown is the effect of deficit irrigation on subsequent yields of the following year. Thus, an experiment was conducted to determine the ET_c difference between fully-and deficit-irrigated alfalfa and to determine the effect of the deficit irrigation on yield of the next year.

METHOD

ET_c was determined in a commercial field for fully-irrigated and deficit-irrigated alfalfa. The fully-irrigated alfalfa was irrigated according to the irrigator's normal practices. The deficit-irrigated treatments consisted of no irrigation during July and August with no fall irrigation and no irrigation during July and August followed by a September irrigation. Each treatment consisted of three alfalfa checks with border checks between the irrigated and deficit irrigated treatments. The border checks were necessary to prevent water flow through cracks in the soil from the irrigated treatments into the deficit irrigated treatments. The field scale approach was used to obtain the field-wide conditions experienced by commercial agriculture. A randomized replicated experimental design was not feasible because of the constraints caused by the use of a commercial field.

The experiment was initiated in 2003, but no ET_c measurements were made at that time. In 2004, the Bowen ratio energy balance method (Todd et al., 2000) was used to determine ET_c. However, the results from this method were unsatisfactory due to problems with the instruments used by this method. In 2005, ET_c was calculated from data measured by the eddy covariance (EC) energy balance method (Tanner et al., 1985) and the surface renewal (SR) energy balance method (Spano et al., 1997). The EC method was used in the fully-irrigated treatment and the SR method was used in the deficit-irrigated treatment with no fall irrigation. Calibration of the SR method was achieved by installing an SR system near the EC system in the fully-irrigated treatment and using the EC data to calibrate the SR method for alfalfa. SR calibration coefficients generally ranged between 0.3 (just before harvest) to 0.4 (just after harvest).

Yield and yield quality were determined by sampling at nine locations in each treatment. In addition, canopy coverage, plant height, and soil water tension were also measured. Canopy coverage was measured with a digital infrared camera (Dycam, Inc., Woodland Hills, CA); soil water tension was measured with Watermark® electrical resistance blocks (Irrometer, Inc., Riverside, CA).

RESULTS/DISCUSSION

Alfalfa Yields

Alfalfa yields of the different treatments are shown in Tables 1, 2, and 3 for 2003, 2004, and 2005, respectively. In 2003, yields of the fully irrigated treatment decreased over time during the period of deficit irrigation (Table 1). Deficit irrigation was imposed starting in July. Yields of the deficit irrigation treatments were substantially smaller than those of the full irrigation, particularly for the 4th and 5th harvests of both deficit treatments. For the 6th harvest, yield of the deficit treatment with a September irrigation was higher than those of the earlier harvests under deficit irrigation. Yield of the 6th harvest of the deficit treatment with no September irrigation also was higher than the earlier yields of that treatment, reasons for which are unclear. However, yields of less than 0.5 tons/acre are uneconomical to harvest, therefore, in reality, the yields of the deficit irrigated treatments were zero except for the 6th harvest of the deficit (September irrigation) treatment.

Table 1. Treatment yields of 2003. The 4th, 5th, and 6th harvests occurred on August 6, September 8, and October 23, respectively. The numbers in the parenthesis are the yield reductions in percent of the full yield.

	Yield (tons/acre)				
	4th Harvest	5th Harvest	6th Harvest	Total	Yield Reduction
Full	1.56	1.35	0.58	3.49	
Deficit (no Sep. irrig.)	0.35 (78)	0.25 (82)	0.43 (26)	1.03	2.46
Deficit (Sep. irrig.)	0.28 (82)	0.16 (88)	0.96	1.40	2.09

Yields of 2004 also decreased over time during the measurement period for the fully irrigated treatment (Table 2). Deficit irrigation, which started at the end of June, resulted in a substantial yield reduction for the 6th and 7th harvests. The practical yield of these harvests was zero since yields less than 0.5 tons/acre are uneconomical to harvest. The September irrigation was omitted this year.

Table 2. Treatment yields of 2004. The 5th, 6th, and 7th harvests occurred on July 16, August 16, and September 24, respectively. The numbers in the parenthesis are the yield reduction in percent of the full yield.

	Yield (tons/acre)				
	5th Harvest	6th Harvest	7th Harvest	Total	Yield Reduction
Full	2.21	1.56	1.14	4.90	
Deficit (no Sep. irrig.)	1.96 (11)	0.25 (84)	0.19 (83)	2.21	2.69

The yields of 2005 of the fully irrigated treatment decreased over time (Table 3). Deficit irrigation started on July 25. Yields of the deficit irrigation were considerably smaller than those of the full treatment. The September irrigation increased the yield of the 7th harvest compared to the deficit (no September irrigation) treatment.

Table 3. Treatment yields of 2005. The 6th and 7th harvests occurred on August 23 and October 6, respectively. The numbers in the parenthesis are the yield reduction in percent of the full yield.

	Yield (tons/acre)			
	6th Harvest	7th Harvest	Total	Yield Reduction
Full	0.65	0.44	1.08	
Deficit (no Sep. irrig.)	0.23 (65)	0.26 (41)	0.61	0.47
Deficit (Sep. irrig.)	0.32 (51)	0.52	0.85	0.23

Crop Evapotranspiration

ET_c increased over time during the first part of 2005 as the climate became warmer (Fig. 1). However, considerable variability existed in the data as a result of day-to-day climate variability. The first harvest occurred on or about April 14 and the last harvest on or about September 30. Just after harvest, daily ET_c decreased to values between 0.08 inches/day to 0.15 inches/day. However, the day-to-day variability sometimes masked the harvest effect, particularly early in the year. Maximum daily ET_c between harvests was about 0.30 to 0.35 inches/day during the summer months. After September 15, ET_c decreased over time.

No irrigation occurred after July 25 for the deficit-irrigated treatment (no September irrigation). ET_c of this treatment continued to decrease over time until about August 25 (Fig. 1). Thereafter, a trend of relatively constant ET_c was found over time. Values of the deficit treatment were similar to those of the full treatment after September 30.

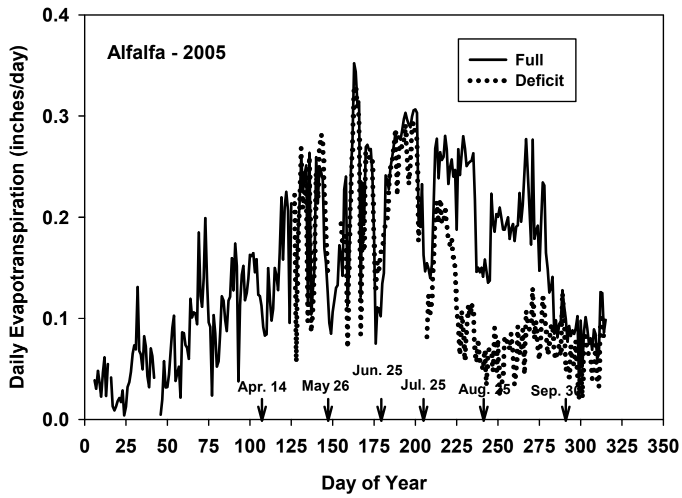

Figure 1. Crop evapotranspiration of fully-and deficit-irrigated alfalfa. The arrows are the harvest dates.

The day-to-day variability in the ET_c data makes it difficult to identify trends in the data. Thus, the data were smoothed using a 3-term moving average (Fig. 2). While the smoothing distorted the data to some degree, the effect of harvest on ET_c is clearly shown. During each harvest, ET_c decreased substantially even though the reference crop evapotranpiration (ET_o) remained high. After September 30, values of ET_c and ET_o were similar.

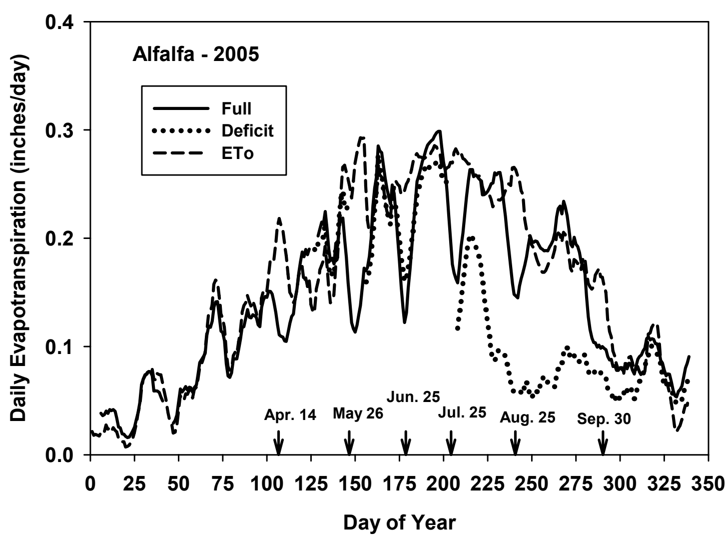

Figure 2. Smoothed crop evapotranspiration using a three term moving average. The arrows are the harvest dates.

Seasonal ET_c of the full treatment was 48.1 inches. Between July 25 and December 6 (end of measurement period), ET_c of the full treatment was 20.8

inches and that of the deficit treatment was 11.4 inches. The difference was 9.4 inches.

Canopy Coverage and Plant Height

Canopy coverage of the fully irrigated treatment varied from between 20 and 40 % just after harvest to between 90 and 100 % just before harvest except after the last harvest (Fig. 3). During the period of deficit irrigation, maximum canopy coverage between harvests was between 55 and 65 %. After the last harvest, canopy coverage of the fully-irrigated alfalfa was about 70% and that of the deficit irrigated area was between 45 and 55 %.

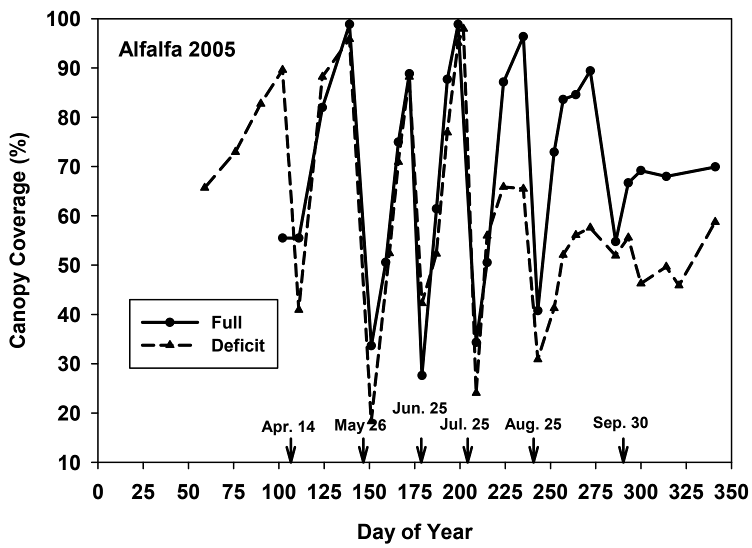

Figure 3. Canopy coverage of fully-and deficit-irrigated alfalfa.

Plant height showed a behavior similar to that of the canopy coverage with values ranging from less than 5 inches just after harvest to generally between 18 and 23 inches just before harvest (data not shown). During the period of deficit irrigation, maximum plant height was less than 12 inches.

Crop Coefficients

Substantial fluctuation in crop coefficients occurred up to the 100th day of the year (DOY100) with many values exceeding two (Fig. 5). Substantial fluctuations also occurred near the end of the measurement period. The average crop coefficient prior to DOY100 was 1.00. Values exceeding 1.5 were eliminated. After DOY100, the harvest schedule affected the crop coefficients over time. Just after harvests, crop coefficients ranged from about 0.3 to 0.5. Maximum coefficients between harvests were about 1.2 (excluding extreme values).

CONCLUSIONS

Deficit irrigation of alfalfa during July and August greatly reduced crop yield. Yields reductions of the deficit-irrigated treatments ranged from 41 to 88 % of the fully-irrigated alfalfa yields. In some cases, the yield was uneconomical to harvest. Deficit irrigation imposed at the end of July 2005 reduced the seasonal crop evapotranspiration by 9.4 inches. Deficit irrigation also reduced the maximum canopy coverage and plant height. Based on visual observations, deficit irrigation in a given year did not adversely affect the following year's yield.

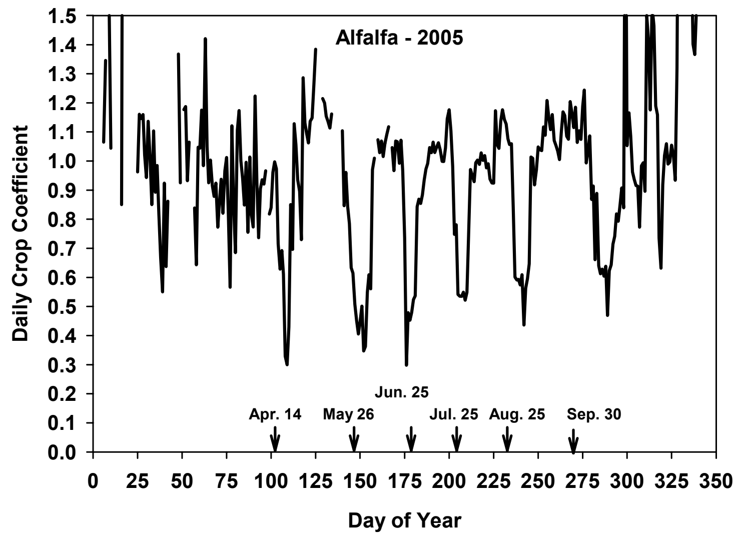

Figure 5. Daily crop coefficients of fully irrigated alfalfa.

REFERENCES

Tanner, B.D., Tanner, M.S., Dugas, W.A., Campbell, E.C., and Bland, B.L. 1985. Evaluation of an operational eddy correlation system for evapotranspiration measurements. American Society of Agricultural Engineers National Conference on Advances in Evapotranspiration, December 16-17, 1985. Chicago, Ill.

Todd, R.W., Evett, S.R., and Howell, T.A. 2000. The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment. *Agricultural and Forest Meteorology* 103: 335-348.

Spano, D. Snyder, R.L., Duce., P., Paw U, K.T. 1997. Surface renewal analysis for sensible heat flux density using structure functions. *Agricultural and Forest Meteorology* 86: 259-271.

JORDAN RIVER RETURN FLOW STUDY

Jason Lillywhite[1], P.E.
Zaffar Eusuff[2], PhD, P.E.

ABSTRACT

The purpose of the Jordan River Return Flow study was to evaluate return flows to the Jordan River due to changes in land use, particularly conversion of land from agriculture to urban, and the effects of future reuse projects on the flows in the River. The study area is located in Salt Lake County, Utah. The Jordan River is an important waterway in Utah because of stakeholder's dependence on the water that flows along its path from Utah Lake to the Great Salt Lake, the most populous area in the state (see Figure 1).

Recently, a group of local water suppliers and wastewater agencies (the Recycled Water Coalition) met and discussed their common interests pertaining to return flows to the Jordan River and wastewater recycling. This study allows the Coalition to consider the flow impacts to the lower Jordan River that may result from changes such as increased wastewater recycling and increased imported water from other outside supply sources. The coalition will use this model to simulate the impact of wastewater recycling on return flows to the Jordan River and discuss options with other water right holders along the river.

The water balance model of the Jordan River Basin was created using CH2M HILL's VOYAGE™ water balance simulation tool. The results of the study show that return flows in the Jordan River have increased since 1945 and will tend to increase in the future. The increase of return flows to the river are mainly due to increases in imported water for Municipal and Industrial (M&I) uses. Canal diversions in the basin have been historically decreasing, and will tend to decrease in the future as agricultural lands are being converted to urban land uses.

INTRODUCTION

Communities along the Wasatch Front depend on a reliable water supply, with an escalating demand for water resulting from population growth and urbanization.

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[1] Water Resources Engineer, CH2M HILL, Salt Lake City, Utah, email: jason.lillywhite@ch2m.com

[2] Water Resources Engineer, Delta Suisun Marsh Office, Division of Flood Management, California Department of Water Resources, Sacramento, CA, email: meusuff@water.ca.gov

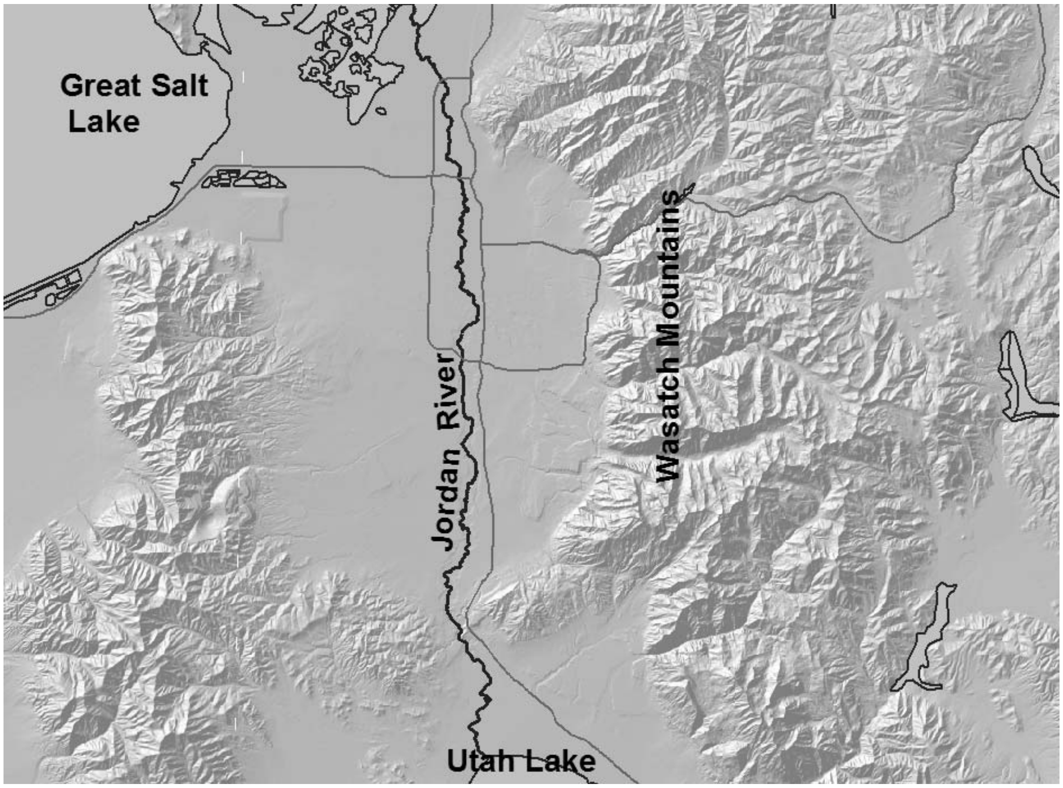

Figure 1. Map of Jordan River, Utah

Planning for future water needs requires an understanding of water supplies, return flows, and the demands for an area with more than 1 million water users.

The user-friendly interface of VOYAGE™ allows users to click points on a map to view all inputs and results, change data, and run alternative scenarios. As evidenced by the responses to the qualifications-based selection, this type of water balance model would typically have been created using Microsoft Excel™ or a commercially available basin model written in a cryptic language like FORTRAN or C++. VOYAGE™ is built on an object-oriented computer language platform that allows the user to see how components of the model interact.

The model was customized to fit site-specific system parameters and characteristics of the Jordan River basin. It characterizes the flows in the Jordan River and allows users to evaluate the effects of future changes in human activity and urbanization. In order to understand how the river is affected, inflows and outflows along the river have been accounted for using a water balance model. The study included the following tasks:

- Collect historic hydrologic and supply/demand data
- Characterize current and historic conditions
- Characterize future demand projections

- Evaluate changes in land use, population, and alternative water supplies, including wastewater reuse
- Quantify return flows to the river

The model was calibrated to year 2003, which is considered as a dry hydrologic year for this area. Different scenarios were modeled for this project, all of which include dry, average, and wet hydrologic model runs. The following scenarios were simulated in this model:

1. Historic: 1945 population and land use
2. Current: 2003 population and land use
3. Future: 2030 population and land use
    a. With 18,000 acre-feet per year (AF/yr) reuse applied
    b. No reuse being applied

A basin-wide accounting of the historic return flows to the Jordan River has not historically been done; however, results from previous studies helped estimate the quantity of return flows to the river. Return flows consist of natural inflow from groundwater, storm drains and tributaries, wastewater effluent, agricultural return flows, and municipal return flows. The water balance model accounted for these factors using historic data, studies, and reports. The projected 2030 simulation was based on a calibrated model of year 2003.

This project does not include a hydrologic or hydrogeologic analysis, but accounts for data obtained from stream gage data and simulations from previous groundwater studies. Figure 2 is a screen capture of the VOYAGE™ Jordan River model.

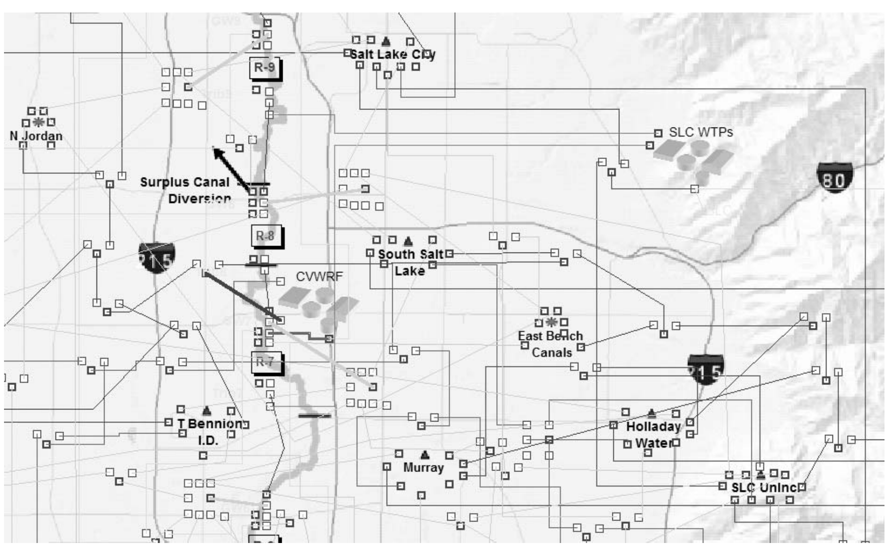

Figure 2. Screen Capture of the VOYAGE™ Jordan River model

THE JORDAN RIVER VOYAGE™ MODEL

Jordan River and Tributaries

The Jordan River was divided into 11 reaches to provide distinct locations for calculating water balance in the river. The water balance model was set up to display graphical output of flows for each reach.

Releases from Utah Lake into the headwater of Jordan River were simulated in the model. The interaction between Utah Lake and Jordan River is one of the most important aspects of the water balance model since it is tied directly to the flows in the river. The Utah Lake drainage basin is partially regulated, and in the future, the regulation and control of the runoff into the lake will likely increase. An algorithm was built into the model to simulate a set of complex rules that govern releases from the lake.

Flows in the river are regulated for the purpose of serving irrigation supply and other diversions such as industrial demands and duck clubs near the Great Salt Lake. In dry years, the river runs completely dry at the upstream end for a period of time in the summer, but groundwater, stream flows, and return flows replenish the river downstream. Flows at eight locations along the river have been monitored by U.S. Geological Survey (USGS) and Salt Lake County Department of Engineering. Jordan River gage data was used for calibrating the model. Stream and storm drain tributaries to the Jordan River were used for calibration and input to the model. The Jordan River model accounts for flows during wet, dry, and average years for future scenarios. Wet and dry factors were determined using historic data from six different gauged streams and storm drains by comparing dry and wet flow characteristics to average years. These factors were applied to un-gauged tributaries and storm drain outfalls along the river to synthesize artificial wet, dry, or average hydrologic periods.

Water Supplies

Existing supplies serving M&I and agricultural users in the Jordan River Basin consist of the following:

- Natural stream flows from the Wasatch Mountains within the basin
- Surface water from Utah Lake
- Import water mainly from the Provo River Project and the Central Utah Project (CUP)
- Deep groundwater

Anticipated future supplies include additional CUP water, additional Wasatch stream water, shallow groundwater, wastewater recycling, and additional Utah

Lake water. The two main municipal water suppliers are Metropolitan Water District of Salt Lake and Sandy (MWDSLS) and the Jordan Valley Water Conservancy District (JVWCD). These districts wholesale water to their member agencies. Many cities in the basin supplement this wholesale water with their own deep groundwater wells. Salt Lake City treats water from three major Wasatch Streams. In the future, it is anticipated that agricultural water needs will significantly reduce, import water supplies will increase, and surface and groundwater will become fully developed.

Agricultural Water Use and Return Flows

Agricultural demands were modeled using crop demand, or ET, provided by Utah Department of Natural Resources. Crop types in the valley have been combined into the following categories:

- Alfalfa
- Farmsteads/Pasture
- Fruit and Vegetables
- Corn
- Grain/Beans/Seeds
- Grass/Turf
- Other

There are nine major canals that divert water from the Jordan River. Currently, the total land under irrigation has been estimated to be around 22,000 acres, but is anticipated to decrease significantly in the future due to rapid urban development in the valley.

Table 1. Historic and projected irrigated land in the Salt Lake Valley

Year	Total Irrigated Land (Acres)
1945	61,000
1980	50,000
2004	22,000
2030	8,000

Crop demand, or ET, is calculated using crop coefficients (kc) for each month and each crop type. Crop coefficients are based on “Consumptive Use of Irrigated Crops in Utah” by Utah State University. The category “Other” represents areas that are irrigated during the off season, such as duck clubs and industrial water demands that use canal water. Supply, demand, and return flow information can be viewed for any of the agricultural areas in the basin by clicking on an agricultural object in the VOYAGE™ model. Figure 3 is a screen capture of the window that appears after clicking on this object.

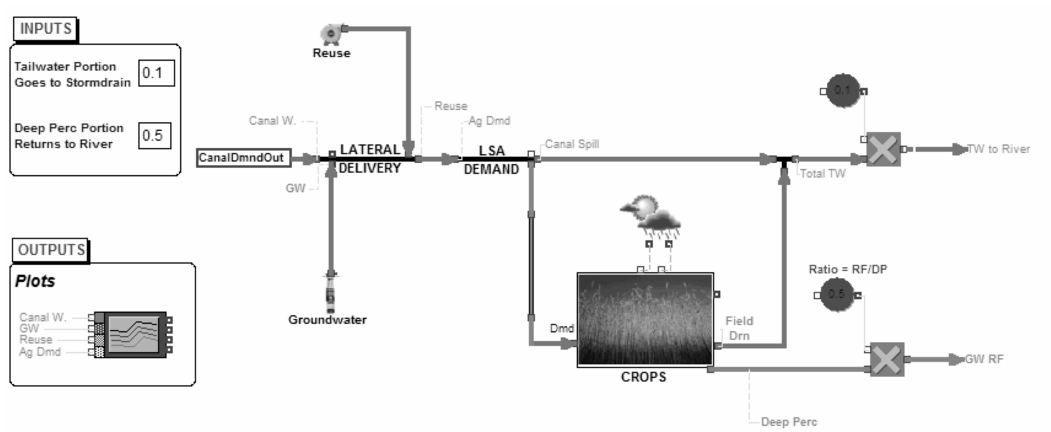

Figure 3. Screen Capture of the Agricultural Supply and Demand Editor

The agricultural object window consists of visual nodes and links that represent the process of irrigation and return flows for the agricultural areas. Crop acres and irrigation methods can be edited by clicking on the "Crop Demand" block.

Figure 4 is a screen capture of the Crop Demand block in the VOYAGE™ model.

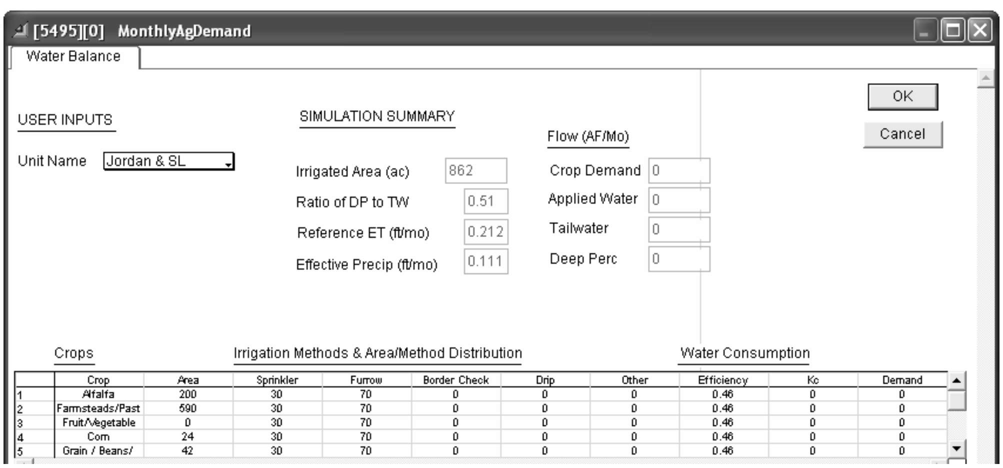

Figure 4. Screen Capture of the Crop Demand Editor

Agricultural return flows consist of surface and groundwater flows to the Jordan River. From model calibration, it was found that for year 2003, overall irrigation efficiency was likely 60 percent for sprinkler and 40 percent for flood. On top of this efficiency, it was determined that a significant portion of canal water was released out the end of the canal as tailwater. For this model, it was assumed that up to 20 percent of the canal flow was lost to tailwater. Table 2 summarizes other inputs used for each canal.

Table 2. Agricultural Irrigation Losses

Canal Name	Irrigation Method	% of Tailwater to river	% of total Deep perc to river
BRIGHTON CANAL	0% sprinkler, 100% flood	20%	30%
DRAPER/SANDY CANAL	100% sprinkler	100%	80%
EAST JORDAN CANAL	30% sprinkler, 70% flood	100%	80%
EAST BENCH CANALS	30% sprinkler, 70% flood	100%	70%
WELBY CANAL	70% sprinkler, 30% flood	20%	40%
JORDAN & SL CANAL	30% sprinkler, 70% flood	100%	80%
NORTH JORDAN CANAL	30% sprinkler, 70% flood	10%	50%
SOUTH JORDAN CANAL	30% sprinkler, 70% flood	50%	80%
UTAH & SL CANAL	30% sprinkler, 70% flood	50%	80%
UTAH LAKE DIST. CANAL	30% sprinkler, 70% flood	30%	70%

M&I Water Use and Return Flows

The water balance model accounts for 22 separate M&I water demand entities, including municipalities and retail water districts in the valley. Demand is calculated as a function of population. Population numbers were obtained for years 1945, 2003, and 2030 and input into the model to estimate M&I water demands. Current indoor per capita demands are estimated to range between 60 and 200 GPCPD. Outdoor per capita demands are estimated to range between 100 and 300 GPCPD, with overall demands ranging between 180 and 400 GPCPD.

Inflow and infiltration (I/I) to sewer collection systems in the valley was accounted for in the model by developing a relationship between indoor water use and recorded wastewater flows. The effect of precipitation and spring runoff on sewer I/I is evident by the increase of sewer flows beginning in the early spring and lasting well into the summer. Municipal return flows include water that returns to the river within the shallow groundwater aquifer, through storm drains, and at wastewater treatment plant discharge points. Return flows originate from both indoor and outdoor uses, including flushing toilets, faucets, showers, and lawn watering. Water supply used indoors, less consumption and losses, flows back to the river via wastewater treatment plants. Water supply used outdoors returns to the river after being applied to the ground as surface runoff, or percolates into the ground.

Wastewater Reuse

The VOYAGE™ model incorporates water reuse projects in the overall water balance. Various water use areas were selected as an initial assumption of application for reuse. These assumptions will likely be modified by members of the Recycled Water Coalition as the planning of these future projects progresses.

It was assumed the total reuse applied in year 2030 is 18,000 AF/yr, which impacts the return flows to the river.

Groundwater

Current groundwater supply in the Salt Lake Valley is limited to prevent mining of the deep aquifer and reduce the threat of degrading the groundwater quality pumped to the surface. Groundwater that flows to the river comes from six different sources, including: (1) seepage from mountain bedrock, (2) underflow channel fill of mountain streams and the Jordan River, (3) seepage from creek channels, (4) seepage from precipitation, (5) seepage from irrigation on the valley floor, and (6) seepage from canals. For modeling purposes, groundwater inflow to the Jordan River was split into two categories including natural groundwater and irrigation return flow.

For modeling purposes, groundwater inflow to the Jordan River was split into two categories: natural groundwater inflow (the first four of the list above) and irrigation return flow (the last two of the list above). Figure 5 is a graph showing groundwater inflow to the Jordan River for a typical year. The line labeled "GW Inflow (USGS model)" represents the results of the USGS groundwater model (Lambert 1995), which was computed on a yearly time-step. The line labeled "Irrigation Return Flow" is a representation of calculated seepage from agricultural irrigation, lawn watering, and canal seepage.

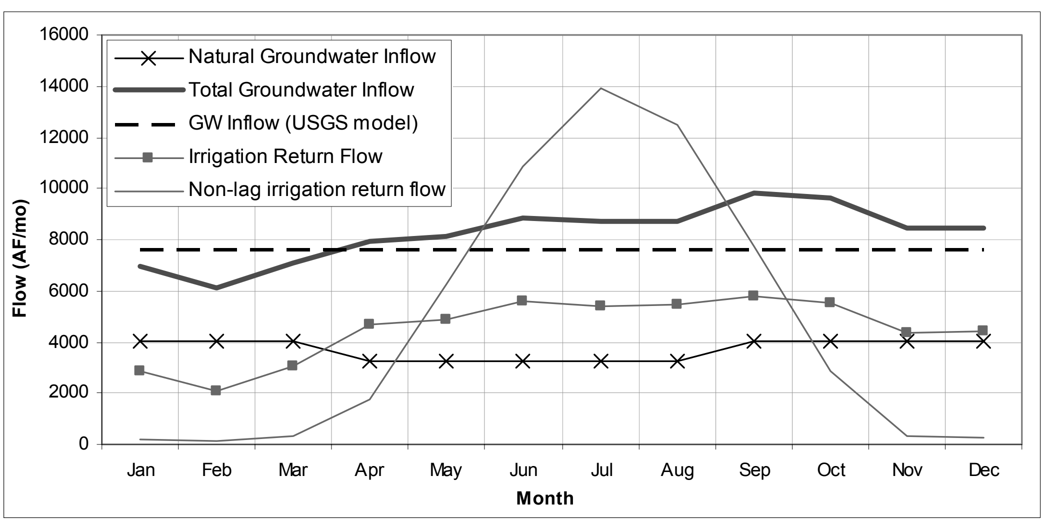

Figure 5. Simulation of Groundwater Inflow to the Jordan River

The total calculated groundwater inflow for the year based on the USGS model is 92,000 AF. From the results of the VOYAGE™ model, it was determined that the natural groundwater inflow is approximately 40,000 AF/yr and the approximate return flow component is 53,000 AF/yr.

Model Results

The results of the model indicate that overall flows in the Jordan River tend to increase over time. The increase in flows is mainly due to increased imported water to the basin. Results of the VOYAGE™ model can be viewed in the model itself by opening a series of tables and graphs within various nodes and blocks. A final version of the VOYAGE™ Jordan River model was provided to members of the Coalition with documentation of the methodology, criteria, assumptions, and results of the model. Figure 6 is a graph showing a comparison of flow in the lower Jordan River for years 1945, 2003, and 2030, all of which are assumed or known to be dry years. This graph is automatically linked to the output of the model, so whatever scenario the user runs can link to this plot. The table is set up to graph the following scenarios:

1. R1 = 1945 dry year
2. R4 = 2003 dry year
3. R7 = 2030 dry year
4. R10 = 2030 dry year with no reuse projects
5. 2003 gauged flow (this plot will not change automatically)

As shown in the graph, total flow in the river has increased since 1945 due to increases in import water supply for M&I use and decreases in agricultural irrigation diversions. A slight decrease of flow in the river will likely occur when the projected wastewater reuse is put in use.

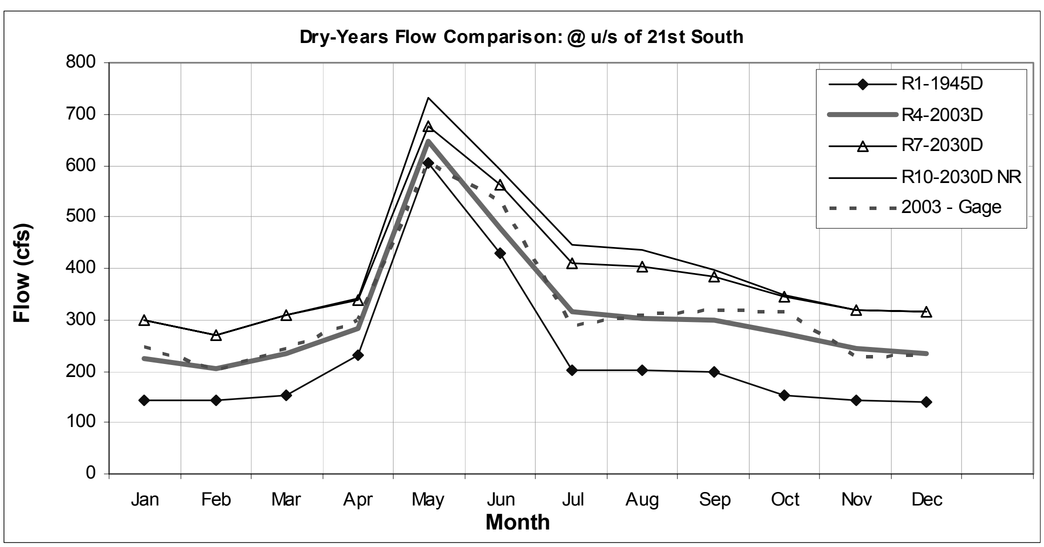

Figure 6. Flow comparisons in the lower Jordan River

REFERENCES

Utah Department of Agriculture (UDOA). 1993. Utah Agricultural Statistics: Utah Department of Agriculture Annual Report. Salt Lake City, Utah.

Bureau of Economic and Business Research (BEBR). 1963. *Use of Water for Municipal and Industrial Purposes: Utah Counties 1960– 1961.* U.S. Bureau of Reclamation.

Division of Water Resources (DWR), Utah Department of Natural Resources. 1994. *A Water-Related Land Use Inventory Report of the Lower Jordan River Study Area.* Salt Lake City, Utah.

Division of Water Resources (DWR), Utah Department of Natural Resources. 1999. *A Water-Related Land Use Summary Report of the State of Utah.* Salt Lake City, Utah.

"Salt Lake Valley Ground-Water Management Plan Update: Ground-Water Use for 1996 through 1999 2000.

Burden, C.B., et al. 2004. *Ground-Water Conditions in Utah, Spring of 2004.* Cooperative Investigations Report Number 45. Salt Lake City, Utah: Utah Department of Natural Resources Division of Water Rights.

Lambert, P.M. 1995. *Numerical Simulation of Ground-Water Flow in Basin-Fill Material in Salt Lake Valley, Utah.* Technical Publication No. 110-B. United States Geological Survey, Utah Department of Natural Resources Division of Water Rights, and the Utah Department of Environmental Quality Division of Water Quality.

THE *WATER 2025* CHALLENGE GRANT PROGRAM PREVENTING CRISES AND CONFLICT IN THE WEST

Megan Montague[1]
F. Jeffrey Peterson[2]
Chris Jansen Lute[3]

ABSTRACT

Water 2025 is a key focus of the Department due to the critical role that water plays in the 17 western states. The accomplishments of the Program during its first three years demonstrate its effectiveness in addressing water management issues in the West. *Water 2025* is based on the reality that the demands for water in many western basins exceed the available supply. The *Water 2025* Challenge Grant Program helps launch local collaborative efforts to stretch existing water supplies by awarding Federal funding on a 50/50cost-share basis, through a competitive process. Eligible grant applicants include States, Tribes, irrigation districts, water districts or other organizations with water delivery authority. The Program helps fund creation of water markets, water banks, and water conservation measures that make more efficient use of existing water supplies.

INTRODUCTION

Water is the lifeblood of the American West and the foundation of its economy. It is also the scarcest resource in some of the fastest-growing areas of the country. *Water 2025* is intended to focus attention on the reality that explosive population growth in western urban areas, the emerging need for water for environmental and recreational uses, and the national importance of the domestic production of food and fiber from western farms and ranches are driving major conflicts between these competing uses of water. The Program provides a basis for public discussion of the realities that face the West, so that decisions can be made at the appropriate level in advance of water supply crises. It also sets forth a framework to identify the problems, solutions, and a plan of action as the Department of the

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[1] Civil Engineer and Water Conservation Program Specialist, U.S. Bureau of Reclamation, Pacific Northwest Regional Office 1150 N. Curtis Road, Boise, ID 83706; mmontague@pn.usbr.gov.
[2] Civil Engineer and Water Conservation Program Specialist, U.S. Bureau of Reclamation, Pacific Northwest Regional Office 1150 N. Curtis Road, Boise, ID 83706; jpeterson@pn.usbr.gov
[3] Program Manager, Water Resource Management, U.S. Bureau of Reclamation, Pacific Northwest Regional Office 1150 N. Curtis Road, Boise, ID 83706; cjansen@pn.usbr.gov

Interior (Interior) works with States, Tribes, local governments, and the private sector to meet water supply challenges.

In some areas of the West, existing water supplies are, or will be, inadequate to meet competing demands for water, even under normal water supply conditions. *Water 2025* recognizes that States, Tribes, and local governments should have a leading role in meeting these challenges, and that Interior should focus its attention and resources on areas where scarce Federal dollars can provide the greatest benefits to the West and the rest of the nation.

An important aspect of *Water 2025* is the Challenge Grant Program. Challenge Grant funding is provided on a 50/50 cost-share basis to irrigation and water districts, Western States, Tribes, and other entities with water delivery authority, for projects that stretch existing water resources. Challenge Grant projects focus on modernizing aging water delivery infrastructure, improving water use efficiency and conservation, and marketing water. Projects are selected through a competitive process, with an emphasis on projects that will achieve demonstrated results within 24 months from the date of award.

In 2004 and 2005, the first two years of the Program, the *Water 2025* Challenge Grant Program provided funding for 68 projects that represent approximately $58 million in water system and water management improvement across the West, including non-Federal cost-share contributions of approximately $44 million and a Federal investment of approximately $15 million. In other words, for every dollar the Federal government has invested, there has been about $3 non-Federal investment.

In FY 2006, for the third year in a row, Reclamation received more than 100 proposals for Challenge Grant funding. The proposals represent a combined request of over $19 million in Federal funding to complete more than $63 million in water delivery system improvements across the West (including non-Federal cost-share amounts). With $1.3 million available for the FY 2006 Program, Reclamation selected 10 projects for award. Including the matching contributions of non-Federal partners, the selected 2006 projects represent a combined investment of more than $5.6 million in water management improvements.

Water 2025 **Projects in the Pacific Northwest**

In just three years since the inception of the Program in 2004, Challenge Grants have been awarded for 17 projects located in the Pacific Northwest. These projects represent creative, collaborative solutions to local water supply issues that use Federal dollars to leverage private funding.

By way of example, in 2005, the Swalley Irrigation District in Central Oregon received a *Water 2025* grant for a project that includes a total of 19 Irrigation

Districts throughout Oregon, Idaho and California. This project entails use of GIS technology in direct support of water conservation planning, development and implementation to improve irrigation system efficiency. It is estimated that this project could result in water savings of up to 165,000 acre-feet annually.

On July 10, 2006, Secretary Kempthorne awarded *Water 2025* Challenge Grants to the Three Sisters Irrigation District ($300,000) and the Central Oregon Irrigation District ($99,937) for projects that will improve efficient use of existing water supplies through conservation, efficiency and water market programs.

The Three Sisters Irrigation District, which previously received a *Water 2025* grant in 2005 for Phase I of the McKenzie Canyon Project, will use its FY 2006 Challenge Grant to implement Phase II by installing 11,300 feet of pressurized pipe to replace an existing open canal. When completed, it is estimated that Phase II could save up to 750 acre-feet of water per year. The Central Oregon Irrigation District, which received a *Water 2025* grant in 2004 for the formation of the Central Oregon Water Bank with the Deschutes Water Alliance, will use its FY 2006 Challenge Grant to expand the operations of the bank. Activities will include development of an on-line water rights management system, development of a storage program for the water bank, and further capitalization of reserves and bank operations.

Water 2025 Challenge Grants for Western States

In 2006, Reclamation initiated the Challenge Grant Program for Western States. This component of the Program provided an opportunity for State governmental entities with water management authority (e.g., State Departments of Water Resources, State Engineers' Offices, etc.), located in the 17 Western States, to compete for *Water 2025* Challenge Grant funding. Eligible projects include on-the-ground conservation and efficiency projects like those funded under the regular Challenge Gant Program (canal lining, measuring devices, SCADA systems, etc.); water marketing projects, and analytical tools to improve water management, which could include modeling, supply and demand forecasting and/or system optimization reviews. System optimization review projects involve an analysis of a particular basin or area with recommendations for improvements to optimize efficiency.

Six Western States Challenge Grant projects were funded in 2006, including one awarded to the Idaho Water Resource Board. Cost shared funds for this project will be used to design and construct a pilot aquifer recharge project to store surface water from the Upper Snake River Basin in the Eastern Snake Plain Aquifer for later use. This project will enable the annual storage of up to 10,000 acre-feet of surface water from the Upper Snake River Basin within the aquifer.

System Optimization Reviews

In Fiscal Year 2007, the System Optimization Review (SOR) component of the *Water 2025* Program will be formally initiated. The SOR component will provide funding on a 50/50 basis to irrigation and water districts, western States, Tribes, and others with water delivery authority to assess the potential for water management improvements in a given basin or district. The purpose of SORs is to ensure that existing water supply infrastructure is fully utilized within the framework of existing treaties, interstate compacts, water rights, and contracts.

Each SOR will consist of an analysis of a water basin, district or system, or a portion thereof, and the preparation of a report recommending improvements to optimize efficiency. The focus of the SOR will vary depending on the stage of the planning process being addressed. Some water users may require a system-wide analysis, considering various options for improving water management. Other water users that have already done some system-wide planning (e.g., water conservation plans) may wish to update an earlier plan and focus the analysis on a particular type of project, such as water marketing or automation.

The improvements identified in the SOR report may be physical, including system automation, measurement, or canal lining or piping, for example. Other options may be operational, involving modification of district policies or procedures to facilitate water transfers, utilizing water markets, or otherwise improving water management. The recommended actions should be practical, affordable, consistent with any state-wide, basin-wide or local water plans, consistent with the applicant's needs and objectives, and tailored to local conditions.

Consistent with the *Water 2025* goal of reducing conflict, partnerships among water delivery entities, local, state, tribal and Federal agencies and other stakeholders will be considered and encouraged, where appropriate, in the development of the SOR recommendations.

THE FUTURE OF *WATER 2025*

On April 6, 2006, U.S. Senator Pete Domenici introduced S. 2561, a bill to provide permanent authorization for the Secretary of the Interior (Secretary) to make available cost-shared grants and to enter into cooperative agreements to further the goals of the *Water 2025* Program. On April 25, 2006, U.S. Representative Heather Wilson introduced an identical bill, H.R. 5192, in the House of Representatives. S. 2561 and H.R. 5192 would authorize the Secretary to enter into grants and cooperative agreements with Western States, Tribes, irrigation districts, water districts, or other organizations with water delivery authority. At this time, the *Water 2025* legislation is still pending.

The Fiscal Year 2007 budget request for *Water 2025* was $14,500,000, including $11,800,000 for the Challenge Grant Program and System Optimization Reviews and $2,700,000 for desalination research, allocated through a competitive process on a cost-shared basis for projects to improve desalination technology and reduce its cost.

We encourage you to learn more about the *Water 2025* Program by going to our website at: http://www.doi.gov/water2025/Water%202025-08-05.pdf .

WASTEWATER RECLAMATION AND REUSE IN THE LINCOLN, CALIFORNIA, AREA

W. Martin Roche[1]

ABSTRACT

The City of Lincoln (City), California, located 25 miles northeast of Sacramento, is experiencing rapid growth generated by developer projects in recently annexed areas. The City has recently completed a new wastewater treatment and reclamation facility (WWTRF) for the purpose of treating and disposing of wastewater generated within the City of Lincoln General Plan area. The WWTRF is currently producing an average dry weather flow (ADWF) of approximately 2.4 million gallons per day (mgd) (2,700 acre-feet per year) with an anticipated increase to as much as 6 mgd (6,700 acre-feet per year) over the next 5 to 10 years. At build-out of the current City General Plan, the City is expected to generate an average dry weather wastewater flow of 10 to 12 mgd (11,200 to 13,400 acre-feet per year). The Placer Nevada Wastewater Authority, comprised of Western Placer and Nevada County public agency jurisdictions, is considering expansion of the Lincoln WWTRF as a regional wastewater treatment and reclamation facility. If implemented for this purpose, the total average wastewater flow at an expanded WWTRF could be as much as 25 mgd (28,000 acre-feet per year).

Effluent from the Lincoln WWTRF is of sufficient quality to allow unrestricted reuse, including the farming of salinity sensitive crops. The State Water Resources Control Board (SWRCB), which is empowered to permit and regulate wastewater treatment and disposal facilities, has an established policy encouraging the recycling of effluent to the extent possible, rather than discharging effluent to surface waters or disposing of effluent on land. In order to implement this policy locally, the City authorized a study of the potential for reuse of effluent from its WWTRF. Agricultural properties located in the vicinity of the WWTRF that are suitable for irrigation with the reclaimed water have been identified, and have an estimated demand of 10,700 acre-feet per year. Other potential reuse opportunities include landscape, golf course, and recreation area irrigation and industrial reuse, and have an estimated demand of 5,700 acre-feet per year.

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[1]Consulting Engineer, 13879 Naomi Way, Grass Valley, CA 95945
wmroche@usamedia.tv

INTRODUCTION

The City of Lincoln (City), 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%. The City has recently completed a new wastewater treatment and reclamation facility (WWTRF) for the purpose of treating and disposing of wastewater generated within the City of Lincoln General Plan area. The WWTRF is currently producing an average dry weather flow (ADWF) of approximately 2.4 million gallons per day (mgd) (2,700 acre-feet per year) with an anticipated increase to as much as 6 mgd (6,700 acre-feet per year) over the next 5 to 10 years. At build-out of the current City General Plan, the City is expected to generate an average dry weather wastewater flow of 10 to 12 mgd (11,200 to 13,400 acre-feet per year).

The Placer Nevada Wastewater Authority, comprised of Western Placer and Nevada County public agency jurisdictions, is considering expansion of the Lincoln WWTRF as a regional wastewater treatment and reclamation facility. If implemented for this purpose, the total average wastewater flow at an expanded WWTRF could be as much as 25 mgd (28,000 acre-feet per year).

WASTEWATER TREATMENT AND RECLAMATION FACILITY

The WWTRF (Figure 2) was completed in 2005 at a cost of $85 million. It is designed to treat 3.5 mgd of raw sewage using state-of-the-art processing that meets strict federal and state discharge requirements including the California Toxics Rule. It is the product of a public-private partnership between the City and private developers that created one of the most modern and environmentally friendly wastewater treatment plants in Northern California.

The Treatment Process

The treatment process begins with screening and solids removal. Next is secondary treatment using the activated sludge process consisting of anoxic basins, oxidation ditches, secondary clarifiers, and a return activated sludge pump station. Effluent from the secondary clarifiers is then pumped to maturation ponds that act as equalization basins for handling fluctuation flows, metals and other constituent concentrations. The ponds have a capacity of 180 million gallons (550 acre-feet). Dissolved air flotation thickeners treat the wastewater effluent from the maturation ponds and in some cases, from the tertiary storage basins, to remove algae growth during storage. A coagulant is then added to allow remaining fine suspended particulates to agglomerate into flocs. The mixed

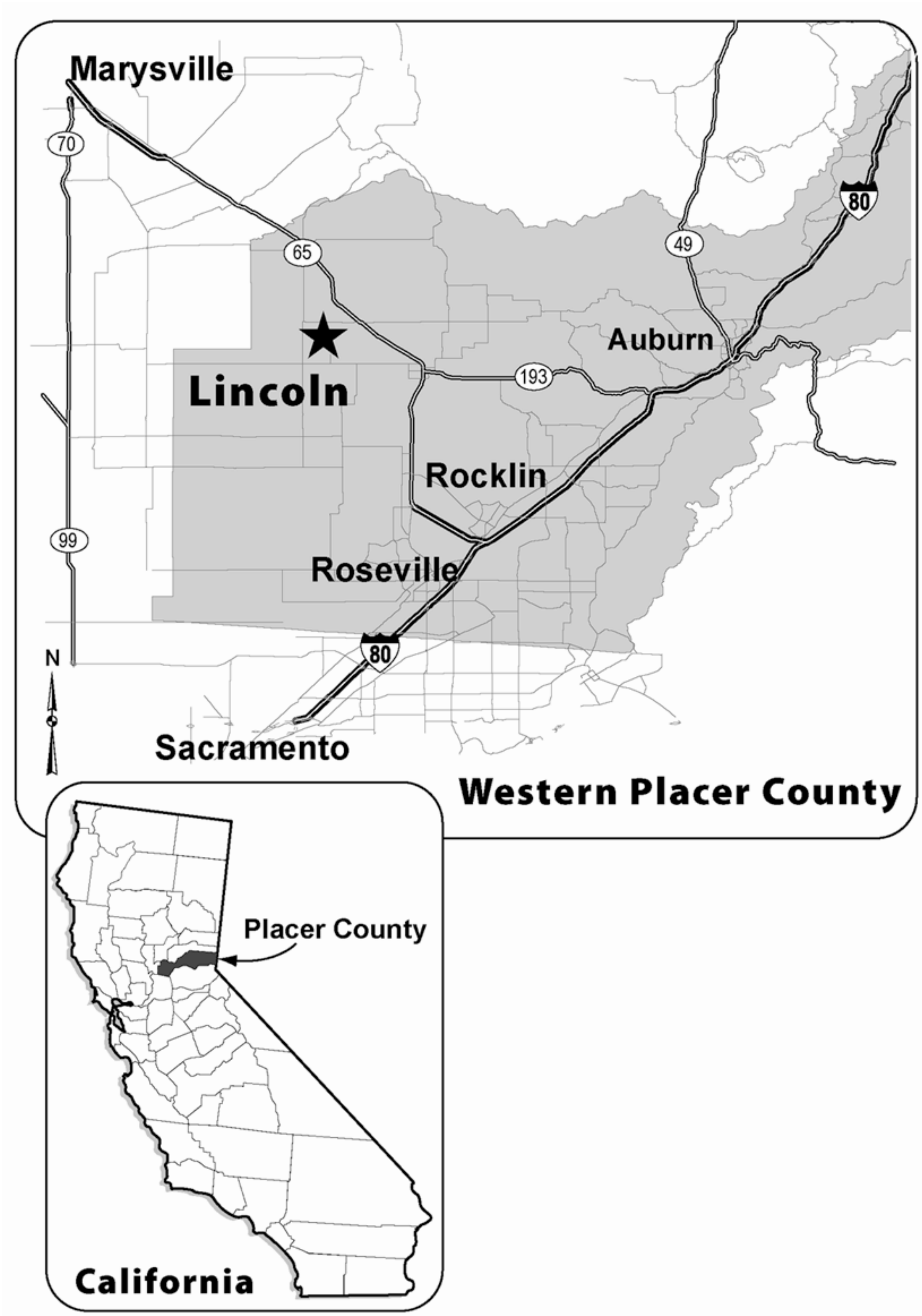

Figure 1. General Location Map

effluent flows to filters where the flocculated particles are removed as the water flows through granular media. Finally, disinfection is required to destroy pathogenic organisms that survive the other treatment processes. The filtered wastewater effluent is passed through channels equipped with ultraviolet (UV)

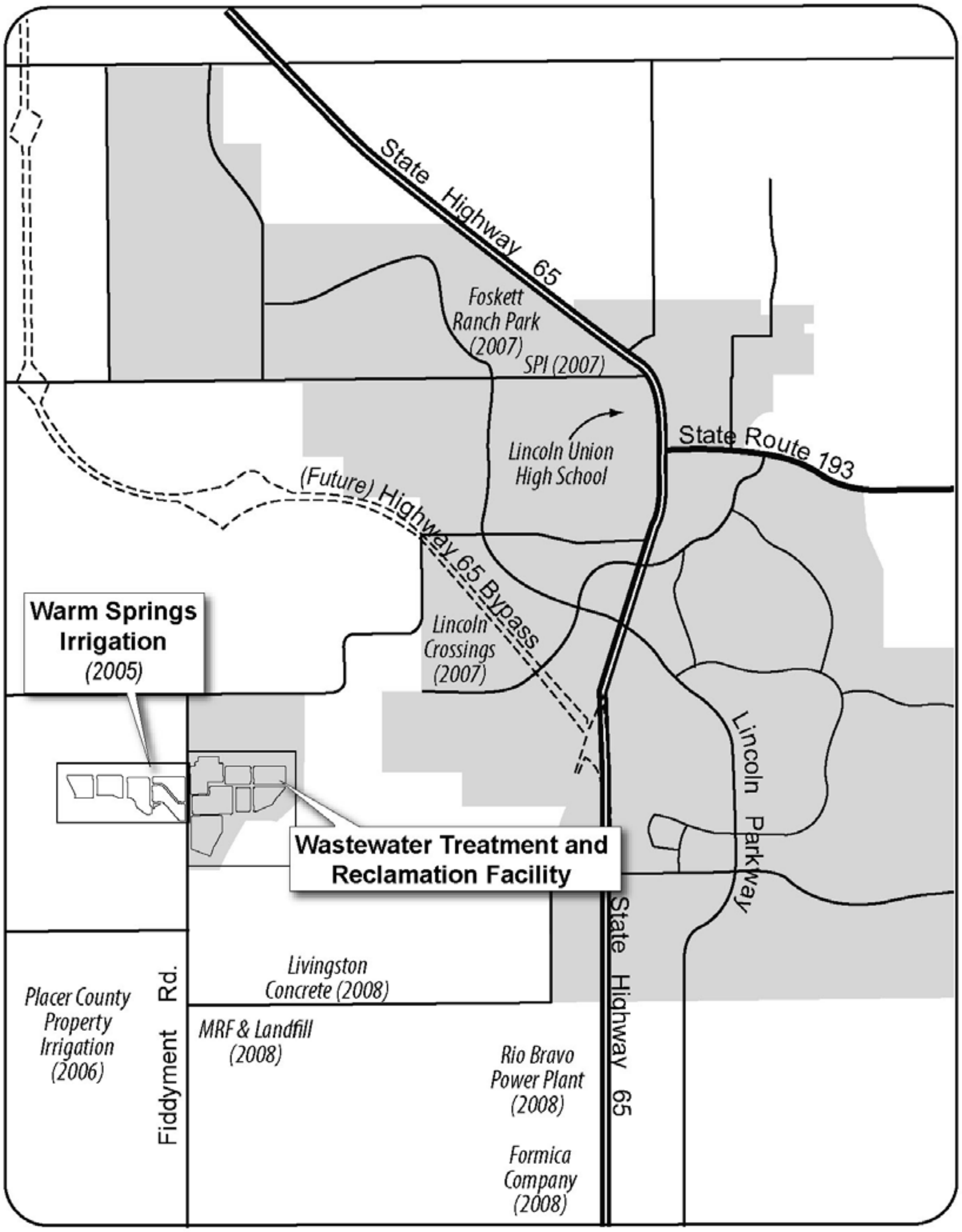

Figure 2. Wastewater Treatment Facility and Reuse Locations

light lamps that expose the pathogens to UV radiation, which provide disinfection without the chlorine by-products found in typical wastewater treatment plants.

Waste solids are generated during the activated sludge, filtration, and dissolved air flotation processes. The solids are dewatered and collected for hauling to off-site disposal. The solids treatment facilities include a solids holding tank, a solids feed pump station, dewatering centrifuges, and truck loading ports.

Effluent Distribution

Fully treated effluent can be delivered to several discharge or reuse sites, depending on the time of year. The effluent pump station pipelines convey effluent to an outfall discharge into the habitat sensitive Auburn Ravine Creek, to designated agricultural or landscape irrigation sites, to future industrial uses, or to temporary on-site storage ponds. The ponds have a capacity of 180 million gallons (550 acre-feet). Because of the WWTRF's ability to produce reclaimed water of the highest quality, it has become a key element to maximize water reuse in the area.

REGULATORY REQUIREMENTS FOR REUSE

Water Quality Control Board Requirements

The effluent produced by the Lincoln WWTRF is subject to a permit issued by the California Central Valley Regional Water Quality Control Board (RWQCB). The Waste Discharge Permit contains effluent limitations for BOD, TSS, and priority pollutants and receiving water limitations for temperature, turbidity, pH, and dissolved oxygen concentration for effluent discharged into Auburn Ravine Creek. For example, the effluent limits for BOD are 30 mg/l monthly average, 45 mg/l weekly average, 60 mg/l daily maximum, and 85% removal on a monthly basis. The receiving water limitations for pH are for the discharge to not cause the pH to fall below 6.5 or to exceed 8.5 or to change the pH by more than 0.5 units on an annual basis.

Health Related Water Quality Requirements

Health related water quality requirements for recycled water are defined by the California Department of Health Services (DHS) regulations known as Title 22 that was last revised in 1999. Title 22 defines the allowable uses of recycled water based on the level of treatment provided by the wastewater treatment process. The effluent produced by the Lincoln WWTRF will be oxidized, coagulated, clarified, filtered, and disinfected to 2.2 most probable number (mpn)/100 milliliters (ml) of total coliform organisms conforming to Title 22 unrestricted reuse criteria. According to Title 22, such effluent can be used for the following purposes:

1. Irrigation of food crops, including all edible root crops, where the recycled water comes into contact with edible portions of the crop.
2. Irrigation of parks and playgrounds.
3. Irrigation of schoolyards.
4. Irrigation of residential landscaping and unrestricted access golf courses.
5. As a source of water supply for non-restricted recreational requirements.

On an emergency basis, recycled water can be discharged to specified "secondary-23" reclamation areas if the (mpn)/100 milliliters (ml) of total coliform organisms exceeds 2.2 but does not exceed 23.

EXISTING REUSE

The WWTRF currently makes use of two land disposal and water recycling sites, totaling 372 acres, (Table 1, and Figure 2). The reuse at the Warm Springs site began in 2005 shortly after the completion of the WWTRF. Reuse at the Placer County Property began in a testing mode in 2006 and will be fully operational in 2007.

Table 1. Existing Wastewater Reuse

Project	Irrigation Method and Crop	Acres	Demand in Acre-Feet per Year
Warm Springs	Flood Irrigation	117	400
Placer County Property	Center Pivot Irrigation	255	875
Total		372	1,275

POTENTIAL FOR REUSE

In addition to the above current City-controlled agricultural reuse, the following reuse opportunities exist.

Private Agriculture

There are over 3,000 acres of agricultural land capable of using over 10,700 acre-feet per year of reclaimed wastewater.

Golf Courses

There are four golf courses in the vicinity of the City of Lincoln that could use up to 1,635 acre-feet per year of wastewater from the WWTRF.

Landfill and Material Recovery Facility

The Placer County Western Regional Landfill and Material Recovery Facility (MRF) can use 85 acre-feet per year of wastewater for dust control, landscape irrigation, and vehicle washing.

Industrial Users

There are four potential industrial users located within the planning area that could use 1,635 acre-feet per year of wastewater on a year-around basis. The Sierra Pacific (SPI) Lumber Mill could use 485 acre-feet per year to spray on timber to prevent drying and for an on-site power generation facility. The Rio Bravo Power Plant could use 485 acre-feet per year. The Formica Company could use 605 acre-feet per year at their local factory. The Livingston Concrete Company could use 60 acre-feet per year for concrete production at their local plant.

City Parks and Recreational Areas

The City of Lincoln is proposing to construct a school and a park that could use 165 acre-feet per year for irrigation of soccer fields and baseball fields.

Street and Highway Landscaping

Street landscaping within the City of Lincoln and along the Highway 65 Bypass could use 520 acre-feet per year.

PROPOSED RECYCLING PROJECTS AND SCHEDULE

Table 2 and Figure 2 give the proposed recycling projects with their schedule, type of use, and demand in acre-feet per year, and cost of delivery facilities.

In 2007, the WWTRF will begin a project to supply 485 acre-feet per year of reclaimed water to Sierra Pacific Industries for industrial use and 365 acre-feet per year of reclaimed water to Foskett Ranch Park, Lincoln High School, and the Lincoln Crossing residential area for landscape irrigation. The project will include over 20,000 feet of pipelines ranging in size from 8 inches to 18 inches, and adding two pumps to an existing pump station. The project will also tie into existing 12-inch and 18-inch pipelines, which previously carried wastewater to the old Lincoln Wastewater Treatment Plant, which has been deactivated. Project costs are estimated at $3,700,000.

In 2008, the WWTRF will begin a project to supply 1,235 acre-feet per year of reclaimed water for industrial use to the MRF, Livingston Concrete, the Rio

Bravo Power Plant, and the Formica Company. The project will include 8,100 feet of 8-inch pipeline and 12,100 feet of 24-inch pipeline and cost $4,500,000.

In 2011, the WWTRF will begin a project to supply 320 acre-feet per year of reclaimed water to the Highway 65 Bypass for landscape irrigation. The project will include 9 miles of 12-inch pipeline and cost $6,800,000.

Table 2. Proposed Recycling Projects and Schedule

Year	Project	Type of Use	Demand in Acre-Feet per Year	Cost of Delivery Facilities
2007	Sierra Pacific Industries	Industrial	485	$3,700,000
	Foskett Ranch Park, Lincoln High School, and Lincoln Crossing	Irrigation	365	
2008	Material Recovery Facility and Landfill	Industrial	85	$4,500,000
	Livingston Concrete	Industrial	60	
	Rio Bravo Power Plant	Industrial	485	
	Formica Company	Industrial	605	
2011	Highway 65 Bypass	Irrigation	320	$6,800,000
Future Years	Rice Irrigation Project	Irrigation	400	To be Determined
Total			2,805	$15,000,000

A 100-acre rice irrigation demonstration project is being considered for future years. The property is near the WWTRF and the operator currently purchases about 400 acre-feet per year of water from the Placer County Water Agency. Using wastewater from the WWTRF could result in a cost savings for the operator. Irrigation of golf courses, which could use up to 1,635 acre-feet per year of reclaimed water, has been deferred due to the distance from the WWTRF to the golf courses and the associated high cost of delivery pipelines. As flow from the WWTRF increases and alternative water supplies become more expensive and limited, these projects will be given further consideration.

CONCLUSION

Wastewater reclamation and reuse in the Lincoln, California area can significantly contribute to meeting the water demand of the area. At build-out of the current City General Plan, the City of Lincoln is expected to generate an average dry weather wastewater flow of 10 to 12 mgd (11,200 to 13,400 acre-feet per year). If the Lincoln WWTRF is expanded as a regional wastewater treatment and reclamation facility, the total average wastewater flow could be as much as 25 mgd (28,000 acre-feet per year).

Agricultural properties located in the vicinity of the WWTRF that are suitable for irrigation with the reclaimed water have an estimated demand of 10,700 acre-feet per year. Other potential reuse opportunities include landscape, golf course, and recreation area irrigation and industrial reuse, and have an estimated demand of 5,700 acre-feet per year. Existing and proposed reuse projects would use approximately 4,100 acre-feet per year for agricultural and landscape irrigation and for industrial uses. As water demand increases and water supplies become more limited, additional reuse opportunities will likely be identified.

AN INFRASTRUCTURE MANAGEMENT SYSTEM FOR ENHANCED IRRIGATION DISTRICT PLANNING

Wally R. Chinn[1]
Lawrence Schinkel[2]
Paul Elser[3]
Dave McGee[4]

ABSTRACT

Traditionally, the metered monitoring and quantification of water use by individual irrigators in Alberta has been almost non-existent. As the increasing competition for a limited and finite resource has become much more of a reality in some major river basins, this water management tool is now receiving much more critical attention. In response to that emerging need and a very specific water-sharing issue, a pilot water use-measuring project was devised and implemented within the concentration of just over 6,500 acres of private irrigation along the Canadian reach of the Milk River. This river basin is a unique watershed, rising within the foothills of western Montana, flowing northeastward into and across the southern-most region of Alberta and then back southeastward into northeastern Montana. It is associated with international water management agreements that are a challenge to administer effectively. A rigorous monitoring of water diversions and river flows is critical for the effective administration of the international water-sharing agreement. Of particular concern, for example, is the need to accurately quantify Canadian withdrawals of water that may have originally been diverted up-stream as American allocations. As a result, the Alberta Department of Environment has initiated a project to track instantaneous irrigation water withdrawals along the Canadian reach of the Milk River and have that information reported on a near real-time basis through a designated website.

INTRODUCTION AND BACKGROUND

A History of Irrigation Water Development

Land settlement in the American northwest and Canada's southwest was occurring relatively simultaneously in the latter part of the 19th century. This was

[1] Manager - Irrigation Development; Alberta Agriculture, Food and Rural Development (AAFRD); 100, 5401 – 1st Ave. S., Lethbridge, AB, Canada T1J 4V6; wally.chinn@gov.ab.ca
[2] Senior Monitoring Technologist; AAFRD; 100, 5401 – 1st Avenue S., Lethbridge, AB, Canada T1J 4V6; Lawrence.Schinkel@gov.ab.ca
[3] SCADA Systems Manager; Alberta Environment; Provincial Building, 200 – 5th Avenue S. Lethbridge, AB Canada T1J 4L1; Paul.Elser@gov.ab.ca
[4] District Approvals Manager; Alberta Environment; Provincial Building, 200 – 5th Avenue S. Lethbridge, AB Canada T1J 4L1; Dave.McGee@gov.ab.ca

particularly true in the semi-arid regions of southern Alberta and northeastern Montana in the 1870s through 1890s. To encourage agricultural land settlement, both countries encouraged the development of various irrigation projects that would help sustain the new farming ventures.

The watersheds of the eastern slopes of the Rocky Mountains were envisioned as the sustaining sources of that critical water resource. However, the region's river watersheds have no particular interest in political boundaries so there was some risk that, with the development of some diversions, political issues and some animosities could arise when those diversions by one country were seen to be a potential impact by downstream users in the neighbouring country.

Such was the case with both the St. Mary and Milk Rivers, whose basins and water courses traverse both southern Alberta (in Canada) and northern Montana (in the United States). In fact, in the case of the Milk River, it crosses the international border twice on its meandering journey to enter the Missouri River. Figure 1 illustrates the courses of the St. Mary River (a tributary in the Oldman River Basin, draining to Hudson Bay) and the Milk River (a tributary in the Missouri River Basin, draining to the Gulf of Mexico). These watersheds originate in an area known as the "Crown of the Continent".

In order to establish and protect prior water appropriations, the Canadian Government, in 1898 authorized the development plan for 500,000 acres of irrigation in southwestern Alberta, with the St. Mary River as the source (Gilpin 2000). At the same time, the American Government had laid claim to the Milk River which was relied upon to support irrigation project developments that were in various states of operation along the eastern Milk River valley, dating back, in fact, to the early 1980s (Azevedo 2004). With the implementation of legislation provisions of the American Reclamation Act of 1902, the situation was changing dramatically as American interests also demonstrated specific interests in the waters of the St. Mary River system, laying claim thereto to bolster supplies for their Milk River irrigation project developments. In an analogous fashion, Canadian interests set about, in 1901, to develop plans to divert water from the Milk River to add stability to the water supplies of the Canadian St. Mary Project, supplies that were in jeopardy of being seriously curtailed if American plans were implemented (Gilpin 2000).

By 1902, it was clear that the potential for serious international conflict over these transboundary waters was becoming more and more a reality. At that time, William Pearce was one of the key visionaries and early developers of irrigation projects in southern Alberta. In communications with project financiers and Canadian Government representatives, Pearce speculated that, ". . . the whole question of utilization by another country of international waters is in a very unsatisfactory condition." (Gilpin 2000).

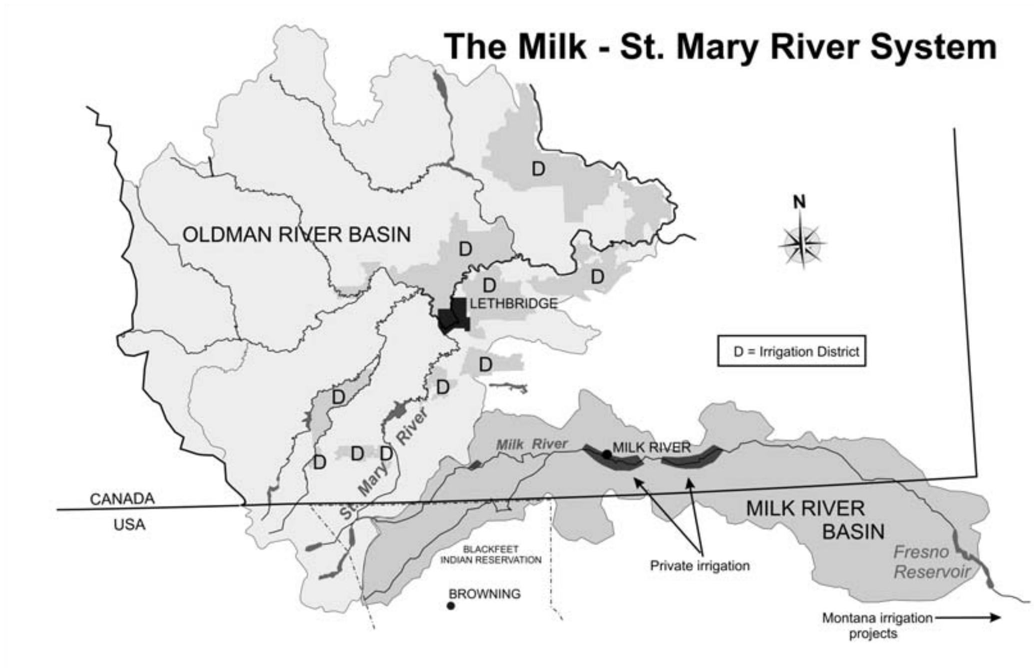

Figure 1. The Oldman and Milk River Basins which share water through international inter-basin transfer.

For example, the most contentious project, for Canadian interests, was the American concept to divert water from the St. Mary River into the Milk River to meet the needs in eastern Montana. In 1902, Canada requested that the U.S not proceed with this proposal as it could prove "injurious to Canadian interests" (Azevedo 2004). However, that request did not return a favourable response and because the Milk River, prior to reaching eastern Montana developments, runs into and through Canada, downstream of that inter-basin diversion, Canada proposed to build and implemented development of another weir. This structure was on the Milk River, just west of the current town of Milk River, and it would divert those waters again, into a newly constructed canal that would flow north and then west to reassure water supplies for the emerging Canadian St. Mary Project. Initial trial diversions took place by 1904. This Milk River diversion scheme was called the Canadian Milk River Canal, within Canada, but was more commonly referred to by the Americans as the Canadian "Spite" Canal (Gilpin 2000). Although this system never carried any water of significance and was never fully completed, for that matter, it had served notice as to its potential capabilities and impact.

INTERNATIONAL BOUNDARY WATERS TREATY

As these impacting issues were becoming quite contentious on both sides of the border, Canada and the USA had already initiated discussions on how best to divide these waters, holding various negotiation sessions late in1902 and again between October, 1903 and June, 1905 (Gilpin 2000). Subsequent to these and other follow-up discussions, a treaty concept concerning these international waters was proposed. As a result of discussions between both countries' federal governments, it was concluded that any such treaty should be able to deal with all internationally-shared waters between the two countries. The result was the signing, in 1909, of the Boundary Waters Treaty. This Treaty also created the International Joint Commission (IJC), which had and still has the responsibility to interpret the meaning, authority and application of various sections within the Treaty (Gilpin 2000).

Figure 2 illustrates the geographical location of the two principle river basins and the inter-basin transfer works developed more than 100 years ago. Today, the St. Mary – Milk River Diversion continues to operate to the primary benefit of American projects in the eastern Milk River Valley, while natural un-diverted flows of the St. Mary River continue to serve irrigation projects in southern Alberta.

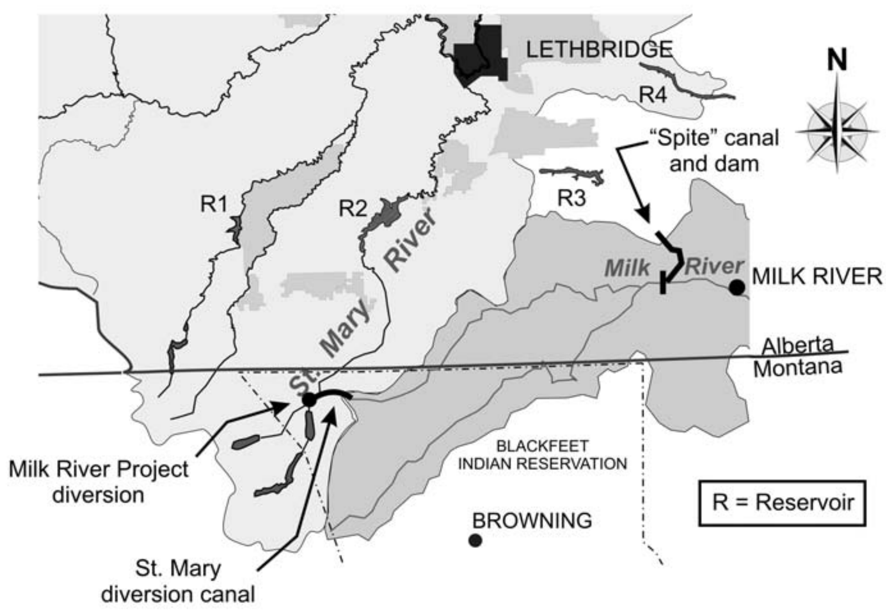

Figure 2. Montana's diversion from the St. Mary River to the north fork of the Milk River, including the location of the 1904 Canadian Milk River or "Spite" Canal.

The 1921 Order

Implementation of the Treaty proved difficult in the years after its signing, particularly as it applied to the situation with respect to the Milk and St. Mary Rivers (Article VI). Many more discussions and negotiations took place over several years, during which time both countries were also fully-engaged in developing their respective water diversion projects. Then, on October 4, 1921, the IJC issued an order respecting the measurement and apportionment of the water of the St. Mary and Milk Rivers.

The Order apportioned flows according to natural flows of the river during the "irrigation season"(April 1st through October 31st) and remaining non-irrigation season, as per the following summary.

a) During the irrigation season, when the natural flow of the St. Mary River at the point where it crosses the international boundary is 666 cfs or less, Canada shall be entitled to three-quarters and the United States to one-quarter of such flow.
b) During the irrigation season, when the natural flow of the St. Mary River at the point where it crosses the international boundary is more than 666 cfs, Canada shall be entitled to a prior appropriation of 500 cfs and the excess over 666 cfs shall be divided equally.
c) During the non-irrigation season, the natural flow of the St. Mary River at the point where it crosses the international boundary shall be divided equally between the two countries.

The Order continued to stipulate, in reciprocal fashion for the Milk River allocations, the same rate of flow criteria and apportioning, except that the proportion of allocations favoured the United States interests.

River Flows and Irrigation In Alberta

Of Alberta's 13 irrigation districts (1.34 million acres) and approximately 290,000 acres of private irrigation, eight of those districts (566,289 acres) and almost 42,000 acres of private irrigation depend on three small rivers (St. Mary, Belly and Waterton) in the most southwestern part of Alberta for their irrigation water supply (AAFRD 2005). These are often referred to as the "Southern Tributaries" of the Oldman River. The water supply to downstream users is reinforced through the inter-connection of these three rivers via a series of on and off-stream reservoirs, connected through large capacity diversion and conveyance canals (Figures 1 and 2). Some of these works are identified in Figure 2, where the labels R1 = Waterton Reservoir (on-stream), R2 = St. Mary Reservoir (on-stream) and R3 = Milk River Ridge Reservoir (off-stream). In addition, this system supplies water for 15 towns and villages, rural domestic supplies, several major agricultural processing and oil and gas industries. The municipal and domestic servicing provides water to support more than 30,000 persons, while several thousand head of livestock also depend on the assured water supplies that this system provides.

It is estimated that the St. Mary River and its on-stream reservoir supplies meet 50 to 60 percent of the annual water demand by all users in the system. As its headwaters are high in the eastern slope mountain watershed of the Rocky Mountains in Montana, its normal hydrology sees a more continuous flow from April through September, peaking, on average, in late May and early June.

River Flows and Irrigation In Montana

Irrigation within the eastern Milk River valley projects of Montana occurs within seven irrigation districts and several Indian Tribe projects. All together, through approximately 660 farms, more than 110,000 acres are irrigated each year. In addition, the Milk River is the source of water for the approximately 14,000 people in the communities of Havre, Chinook and Harlem, Montana (Azevedo 2004). Supply to this eastern reach of the river is stabilized to some degree through the on-stream Fresno Reservoir. Nonetheless, it is the water diverted from the St. Mary River into the North Fork of the Milk River that is the lifeblood for more assured water supplies along the Milk River. However, the Milk River watershed does not originate in the mountains but rather in the foothills and plains east of the Rocky Mountains. Therefore, its primary volume of flow occurs early in the year and generally prior to the main irrigation season. In most years, 70 percent of the Milk River flow near Havre originates as diversions from the St. Mary River basin. In dry years, the St. Mary River diversions can contribute between 90 and 95 percent of the Milk River flows (Azevedo 2004).

Disputing the 1921 Order and Searching for a Resolution

Although both countries share a common history of irrigation water use along and between these two river systems, the extent of development and on-going rehabilitation during that period has been distinctly different. While Canada and Alberta have reinvested nearly one billion dollars in developing, expanding and rehabilitating the irrigation water management infrastructure for the St. Mary Project, the Montana works are still the same basic infrastructure built by the U.S. Reclamation Service in the early 1900s. During that time, diversion and conveyance capacity has decreased and the functional integrity of the whole system is tenuous at best (Azevedo 2004).

Partly as a result of the state of the infrastructure and due to the variable hydrologic nature of the St. Mary flow regimes, the Montana diversions from the St. Mary to the Milk River have seldom achieved the entitlement as defined within the 1921 Order. Figures 3 and 4 illustrate the recent history of those diversions. As can be determined from Figure 4, on average, through the past 33 years, the U.S. has been able to capture or divert only a little more than 65 percent of its entitlement.

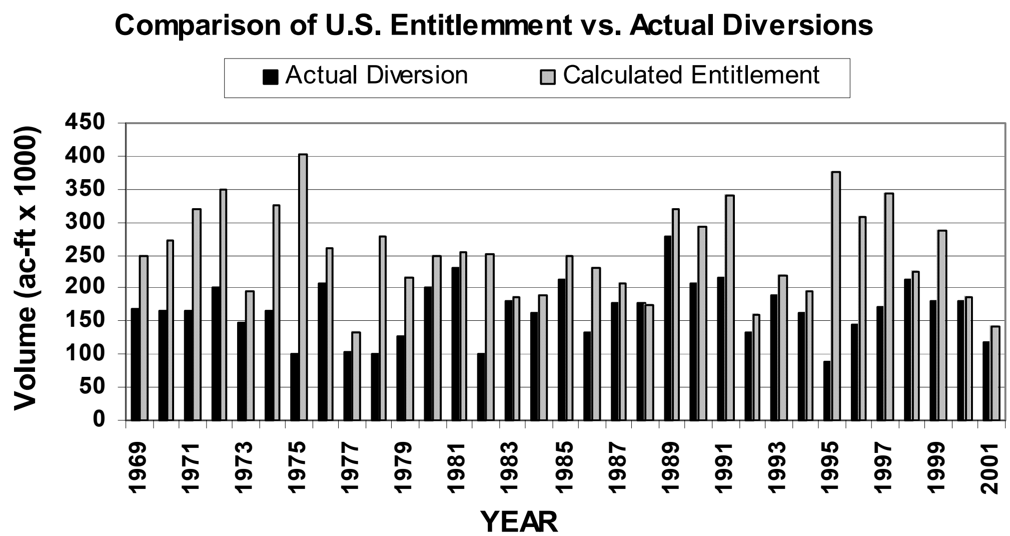

Figure 3. Historical U.S. diversions from the St. Mary River to the Milk River.

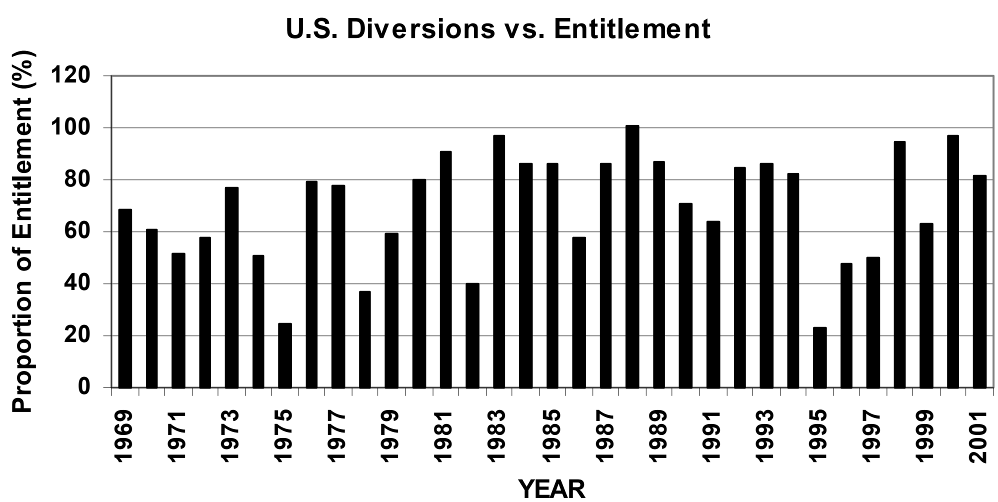

Figure 4. Proportion of actual U.S. diversions from the St. Mary River to the Milk River, relative to the Order entitlement (100%).

Montana has desperately needed to secure capital funding to restore system capacity and reliability. It has also been argued that if the water-sharing arrangement (1921 Order) were re-visited, with the end result providing adjusted mechanisms of apportioning flows that allow Montana to realize a greater portion of its entitlement, Montana could be in a better position to leverage more rehabilitation funding.

In a somewhat analogous fashion, water users along the Milk River in Canada have not been able to divert Alberta's appropriated share, as most of that natural flow occurs and passes on to Montana (Fresno Reservoir and beyond) in early spring, prior to the irrigation season. Therefore, when Alberta irrigators are withdrawing water during the June through August period, for example, it is disputed as to whether the water being diverted is actually Alberta's rightful natural flow entitlement or Montana's diverted St. Mary entitlement. Through all the discussions and renewed negotiations, there has been much conjecture about what Alberta irrigation water users have actually been diverting and whether those diversions are encroaching on Montana's St. Mary diversion entitlements, diversions that can often already be less than the Order allocates to Montana.

NEAR REAL-TIME FLOW MONITORING

Although gross diversions into major irrigation project or district blocks in Alberta are monitored and quantified on a comprehensive basis, measurement of water withdrawals through individual irrigator's works, particularly those outside the irrigation districts, has been quite limited or non-existent. This deficiency has existed despite the requirement for water use licensees to submit annual reports on their past year's consumption. Despite this requirement for annual water use reporting, the direct quantification of actual diversion amounts by individual irrigation water users, through metering, has not traditionally been a formal part of Alberta's water management policies and licensee operations. However, Alberta's recent *Water for Life* water management strategy for sustainability clearly defines an expectation that water use by all sectors will be more comprehensively monitored and reported in the immediate future.

Irrigation in the Milk River Basin – Canada's Portion

The individually licensed and operated irrigation projects, usually associated with single farming enterprises, with diversions from rivers, creeks, lakes, etc., are referred to, in Alberta, as "private irrigation projects". The irrigation diversions that are licensed for withdrawals directly off of the main stem of the Milk River that meanders its way through Canadian territory are typical of these private irrigation projects. There are approximately 50 projects that are authorized to divert water directly from the Milk River itself, for the irrigation of 8,200 acres of agricultural land. Most of these irrigation diversions are located in quite isolated areas which pose their own monitoring challenges.

Almost all of these projects now incorporate closed conduit pumping diversions to supply sprinkler irrigation systems that are primarily centre pivots but also include some wheel-move sprinklers as well. These projects are licensed to divert only that portion of the flow of the Milk River that is deemed to be the Canadian apportionment of the natural flow. However, the recent contentious nature of the water-sharing agreement between the two countries is suggesting that there needs to be a better and more accessible quantification of the actual Alberta irrigators' diversion volumes, for the information and benefit of the interests on both sides of the border.

Individual Pump Diversion Monitoring Systems

In early 2005, the Alberta Department of the Environment (AENV) initiated the development of a prototype water use monitoring and tracking project, specifically designed to encompass all irrigation diversions from the main stem of the Milk River in Alberta. It was intended that the new system would also test a leading-edge water use tracking system that would allow for the use of standard "off-the-shelf" metering systems and also incorporate such telemetry so as to provide near real-time data through a web-enabled configuration that would facilitate the monitoring by an array of interested water management agencies.

By October of 2005, 32 different diversion works (for 6,500 acres) had been outfitted with 40 flow metering devices. (Some sites had multiple diversions.) A mix of representative meter types were installed, including McCrometer in-line propeller meters, Seametrics insertion turbine meters, Seametrics insertion magnetic meters and a Grayline ultrasonic strap-on meter. To meet projected power requirements, all sites were commonly set-up with 50-watt solar panels and 100 amp-hour gel cell batteries. Figure 5 illustrates the conceptual near real-time data link from the meter, through telemetry components to the viewing system.
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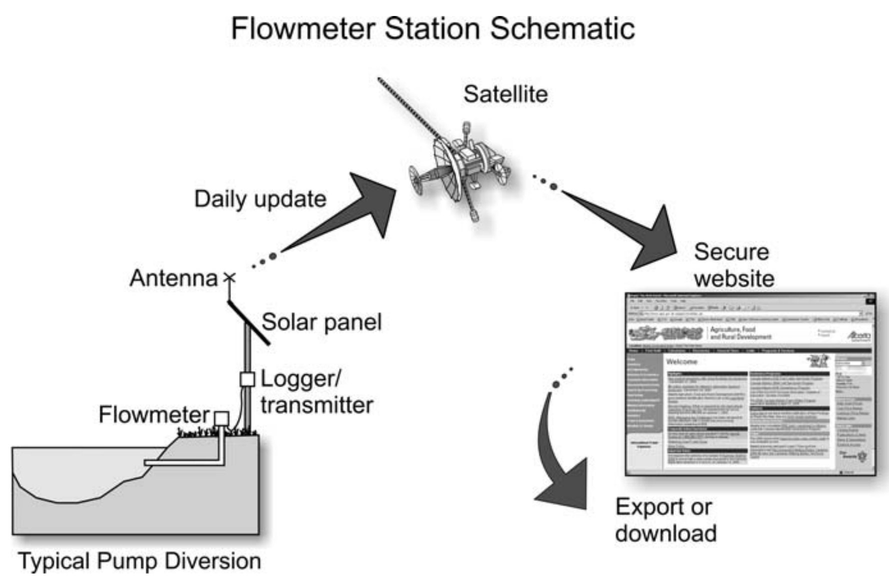

Figure 5. An illustration of the telemetry concept applied to the water use monitoring and tracking system.

Initially, various telemetry systems were installed at only ten of the sites in order that digital up-loads to a project website could be transmitted to develop and test the near-real-time aspect of the monitoring system. Again, the remote and isolated nature of most of these individual pump diversions tasked the enabling of the various telemetry assemblies.

As a result, several different types and configurations of data communication systems were installed for testing. These included:

- 4 ROM Communications systems (3 cellular and 1 satellite)
- 5 Optimum Instruments systems (5 cellular + 2 future satellite)
- 1 Bentek Systems Ltd. (AMCI) satellite-linked system

Both the ROM sites and the Optimum sites include dataloggers to ensure that data is not lost should there be a failure within the telemetry systems

CONCLUSION

The need for a solution to sharing the international waters of the Milk and St. Mary Rivers was the impetus that created the International Boundary Waters Treaty that references all water bodies shared between Canada and the United States. However, despite the solutions derived through recent and past history, it is clear that the escalating competition for water is going to require on-going enhancements of measurement and monitoring technologies in order to better document and quantify actual and finite water diversions and use.

As almost all the equipment and systems for the prototype development project were installed at or after the end of the 2005 irrigation season, there was very limited opportunity to test the installed systems. During the off-season, digital temperature gauges allowed, in a very basic fashion, operation verification of the telemetry components and development of the reporting website. With the start-up of the 2006 irrigation season, metering systems are in operation, equipment deficiencies or system anomalies are being detected and resolved and data is being acquired for further testing of all facets of the project concept.

REFERENCES

Alberta Agriculture, Food and Rural Development (AAFRD). 2005. Alberta Irrigation Information – 2004. Irrigation Branch. Lethbridge, Alberta Canada.

Azevedo, P. 2004. The Need to Rehabilitate the St. Mary Facilities. Department of Natural Resources and Conservation. Helena, Montana.

Gilpin, J.F. 2000. Quenching the Prairie Thirst – St. Mary River Irrigation District. Lethbridge, Alberta Canada

THE WASHINGTON STATE WATER METERING PROGRAM: CHALLENGES, ANSWERS, POTENTIALS, PROMISES

Kenneth B. Schuster[1]

ABSTRACT

The water metering program of the State of Washington began in January of 2002 after the Thurston County Superior Court (the Court) ordered the Department of Ecology (Ecology) to comply with the metering statute at the Revised Code of Washington (RCW) 90.03.360. The Court approved the Ecology plan outlining how Ecology would implement the law and the new rule, Washington Administrative Code 173-173.

This paper discusses how Ecology is meeting the requirements of the Court Order and HR 2860 and to ensure that metering and reporting of data has long-term application. The challenges include 1) defining what needs to be done to satisfy the Court Order, 2) uniformity of data collection to ensure data quality, 3) building a database for storing the data, 4) developing an educational program for meter installers, distributors, water users, the general public, and watershed planners, 5) identifying the universe of uses for the data, and 6) meeting the requirements of HR 2860.

INTRODUCTION

Water and its use, who gets to use it, what uses, when, where, why, how much, and how and who should manage the water resource are the issues in the West. Conversations quickly move to issues of sustainability, economic development, private property rights, water markets, water quality, fish, natural environment, and so on. The issue is close to the hearts and minds of municipalities, agriculture, agribusiness, financial institutions, academicians, politicians, philosophers, and government agencies. It is looking through a dark glass and trying to divine what will be with water for municipalities, irrigators, fish, recreation, environment, to name a few, and how to identify and work with the many issues contributing to the discussion. Where and when do population growth, economic development, government agencies, the public and other interested parties influence the debate?

DEFINING THE ISSUES AND CHALLENGES

Cultural and economic issues drive water law and management of water resources. The seventeen Western states comprise a large land mass popular with

[1] State-wide water metering coordinator, Washington State Department of Ecology, 15 W Yakima Ave, # 200, Yakima, WA 98912; ksch461@ecy.wa.gov.

people for living, outdoor recreation, agriculture, to name a few, with a limited supply of water. The problem is that while humans enjoy living in an arid climate, people want water for creating an artificial humid environment to maximize human comfort. The specialized society created is vulnerable to collapse (DuBos 1968). The West also lives with the myth that it is a land of abundant water, ignoring that the real watershed lands in the West (lands where precipitation exceeds evaporation) consists of only 20% of the total land area and contributes 80% of the water yield (Saunderson 1950; Higbee 1957; Shanks 1984). The mountain snowpack is the primary reservoir for storage of water to be appropriated as it slowly melts during the summer. That works as long as the presumptions upon which society makes its decisions about water storage and use hold. However, those presumptions are weakening and change is needed.

Research by Mote, et. al. (2005) finds that the snow water equivalent in annual snowpack is declining and that the decline is well under way. They conclude that consequences will be profound for water use in regions already contending with the clash between rising demands and increasing allocations of water for fish and wildlife. Water always has been a limiting factor in arid and semi-arid regions, now accepted, but not necessarily recognized, over the last two decades or so.

Smith, et.al. (2002) note that most arguments about use of natural resources are cultural, and that the link between popular opinion and actual policy is weak. Good technical policy usually conflicts with cultural values, resulting in political decisions precluding the evolution of arrangements that may enable parties to bargain over competing uses of resources (Okonski 2006). While sustainable development is the goal, Okonski (2006) notes that sustainable development is a process, not an outcome. Few participants realize or accept that view, making it difficult to develop cohesive policy.

Part of the solution to working with tightening supplies is by increasing and improving the application of technology to improve efficiency of use, realizing that works today may not for the next generation (Henrie 2005A). Henrie further observes that society needs to have faith that solutions can be found in science, technology, and/or modification of human behavior. Harwood (2005) notes the need for new tools, regulatory structures, regional agreements, infrastructure, and planning, and an analysis of demand for water over the long term in order to adapt quickly as situations change. The three-part model for used for planning – water rights, availability of water, and infrastructure (infrastructure includes institutional arrangements and management models in which agencies have developed a level of comfort for getting things done) – may be inadequate if the data and other information needed to make informed choices from that model is lacking.

The most important part of managing water is having accurate, real-time data on water resources and use (Western States Water Newsletter, 2005) for research using quantifiable data to guide development of policy. Henrie (2005B) notes that two years is the minimum time needed to collect and develop meaningful data and have everything functioning properly. Vaux (2005) observes that research needed to solve tomorrow's problems should be initiated today. The research needs to be interdisciplinary using a systems approach, able to accept uncertainty, and designed to be adaptable. Monitoring of streamflow, groundwater, sediment transport, water quality, and water use all must be studied. Given that the role of the Federal government is declining, the responsibility has devolved to the states. The State of Washington is seizing the initiative with its law and regulation on metering water for quantifying its use of water.

THE WASHINGTON STATE WATER METERING PROGRAM

The Water Code of Washington

Waters of the State of Washington are a publicly-owned resource. Users can appropriate and apply water to beneficial uses (most beneficial uses are consumptive uses) identified in Water Code, and are limited to the amount of water they can demonstrate as being put to beneficial use. The present Water Code, enacted in 1917, is a procedural process allowing a user to appropriate water for specific purposes and allows a period of time to establish a water right. A potential water user applies to Ecology for a water right and, if water is available, is issued a permit and a specified time frame to appropriate water to beneficial use. Once development is complete, the user is issued a certificate of water right, and the water becomes appurtenant to the land. Enforcement is done by watermasters, when necessary and/or authorized, on permits, certificated, and adjudicated rights.

Before enactment of the Water Code, water claims were the mechanism used for a user to appropriate water. Rights perfected under the Water Code and active claims are subject to relinquishment or abandonment if non-use exists for a five-year period. Another commonality is "first in time, first in right." Priority on water rights perfected under the Water Code is the date a user submitted an application for a water right, and priority is established for claims by the date on the claims document. Ecology cannot enforce or regulate against claims because claims are inchoate rights.

Enabling the metering program

One of the first requirements to finding the answers to water and its use is a metering program to collect quantifiable data on water use throughout a region or state. The scientific and technical purpose for collecting data is to determine how much is being used and when, and from the data to discern where improvements in water management may derive, particularly to develop and target programs enhancing conservation, such as the Irrigation Efficiencies program of the State of Washington and to improve in-stream flows for fish.

The Washington State Legislature, recognizing the need, amended RCW 90.03 at RCW 90.03.360 and added metering of water use to the Water Code in 1993. All surface diversions and groundwater withdrawals in the State of Washington are subject to the metering law and rule. It requires Ecology to enforce metering on all water diversions, as a condition for all new water rights, and for existing water rights that either 1) are surface water diversions greater than one cubic foot per second, or 2) are diversions or withdrawals from surface and ground water sources that support fish stocks classified as critical and depressed by the Washington Department of Fish and Wildlife. Measuring and reporting return flows is not included in the metering program.

In 1999, Ecology was sued in the Thurston County Superior Court (the Court) for not enforcing the metering law. Ecology wrote a compliance plan for the Court on how Ecology would carry out the Court Order, which the Court approved. Ecology used the three-part model (above) for enacting the program – water rights, availability of water, and infrastructure. WAC 173-173 to promulgate the metering law was completed and published in January 2002 as part of the compliance plan. The approved plan emphasized that the fish-critical basins in the State would be targeted first, with priority given to surface water diversions and to ground water withdrawals in connectivity with surface waters as the law requires. The Legislature provided $3.4 million for cost-sharing the design, purchase, and installation of meters to help users offset costs for compliance.

The three-part model used to meet the Court Order consisted of researching the water rights files and database to determine who held what water right. Availability of water was defined as the total amount of water above one cubic foot per second known to be diverted from each basin. Letters were sent to the holders of the targeted water rights advising the user of the pending requirement to meter and report, followed by another letter containing an administrative order telling the user of the requirement(s) and to begin metering, recording, and reporting. While there were public notices and meetings for writing the regulation in the Washington Administrative Code (WAC) at 173-173 to promulgate the metering law, most users were unaware.

Ecology accomplished its mandate by following a defined and settled procedure to carry out the Court Order. Most regulated businesses work with agency(ies) to meet requirements; it is merely a cost of doing business. Obtaining data on water use from public agencies such as the Bureau of Reclamation, Army Corps of Engineers, hatcheries, power companies, municipalities, and so forth seldom is a problem. It was and is something they do as part of their operational framework.

However, the largest numbers of holders with water rights are private parties and see their water right as a property right. Any intrusion into perceived rights is viewed with suspicion. Often it was the first time many users became aware of the specific details of their water rights. Typical reactions were "is the state intending for me to relinquish my water right," or "is the intent to charge me for my water," to "infringement on my constitutional rights, takings." A common reaction is that a user will divert or withdraw their full water right, needed or not, to demonstrate beneficial use to protect their water right. Research by Benjamin (2006) demonstrates that users do pump or divert all of their rights if they think their water rights are at risk, even though costs are increased. Additionally, Anderson, et.al., (1997) note that conservation can be discouraged because water that becomes surplus through conservation is perceived, rightly or wrongly, as water that must have been wasted in the past and therefore belongs in the stream for other uses (the salvage water rule).

The First Challenge – Enacting the Compliance Plan

Ecology successfully implemented the first part of the compliance plan and moved the metering program to implementation. To address the fears and concerns discussed above, a number of public meetings were held in the affected basins to explain the metering program, answered questions, and discussed the cost-share program and how to apply for funds. It was emphasized that the data from individual users would be available to only the individual users; outside interests could only obtain the data by following the public disclosure process. Also emphasized was that Ecology would develop a database where individual records would be stored and, eventually, users would be able to submit their data over the internet if they chose to do so. Emphasis was placed on the fact that each water user would have an administrative record of water use which would be helpful in the case of adjudications or other legal proceedings. The overall emphasis was to impart to the audience the need for the people of the State of Washington to have reasonably sound data on how much water is used for beneficial uses and how much more may be available for appropriation.

Unless the purpose of collecting data is clearly explained and fears of losing water rights are addressed and a high level of trust and cooperation developed, one cannot be sure that the data submitted represents what is really needed. What is needed to improve trust in the law and the agencies tasked to implement a law or laws is to move away, to deviate, from positional stances and advocacy into a collaborative process. The focus must be on mechanisms and processes that lead to desired outcomes rather than setting precise criteria (Thabault 2005). The whole process must be transparent and subject to outside review. While Thabault was writing about science and protected species, the principle applies to equally to water research.

Levine (2004) agrees, concluding that researchers need to emphasize the importance of stakeholder involvement throughout for improving the quality and perceptions of decisions made at each step. From the standpoint of collecting data from users, an open process is important because, for the State of Washington, the users are given the responsibility of recording and submitting data on water use.

Openness and transparency are therefore important to obtain trust and ensure that data submitted can pass criteria on data quality. How, then, is the Washington State Department of Ecology working on the challenges involved with metering, collecting data, transparency, openness, and developing trust, given the responsibility to enforce the metering law and to implementing the new Columbia River bill, HR 2860?

The Second Challenge - Data Collection and Data Quality

Data accuracy requirements are ± 5% for pressurized pipe systems, and ± 10 % for open channel systems. There will be a high degree of trust from Ecology that water users will submit the right type of data and to be consistent with its collection. The element of trust was emphasized in the public meetings and continues to be emphasized. Rather that focus on whether or not the user is being honest and forthcoming, the emphasis is on educating the water user.

A data quality plan is also being written for use by Ecology to ensure that all data submitted can be scrutinized for quality. Errors in data quality derive from improper installation of meters, improper meter for the system, poor design of systems, lack of expertise on meter design and installation, to users not being instructed in how to read a meter. The immediate emphasis is to get users to report annually even if the data is incomplete or suspect. Once a problem is known, efforts are made to correct the situation. Data quality issues are being identified now and a plan will be in place by the end of 2007.

To help users from the start, Ecology has standardized forms for state-wide use posted on its website that users can download and use to record data, and then submit the completed forms to Ecology at the end of the season of use. Most users are to read and record data weekly and submitted annually the highest monthly instantaneous quantity and the total quantity used each month. However, Ecology encourages users to submit all their readings, and most users do report weekly readings, and some report daily use. Most reports submitted on the standardized forms few errors. If errors are present, it is usually easy to rectify them by calling the water user. Protocols are installed in the database to alert the data entry person if there is an error in submitted data.

To encourage users to collect accurate data, they can access their data in the database after it is received and entered and view it for their own use at any time. That provides the openness needed for developing trust and a sense to users that they participate in the whole process. Several reporting capabilities within the database will be developed later whereby reported water use can be compared to each water right to determine if a water user remains within their water right(s). Ecology also strongly emphasizes the use of data-loggers to ensure consistency of data collection and quality by funding 100% of the cost of data-loggers and devices for downloading data.

The Third Challenge – The Database

Constructing the database was and remains a particular challenge. It is linked to Ecology's Water Rights Tracking System database so that real-time water use data is linked to the appropriate water rights. Protocols are installed to alert when data entry errors occur, ties in the number of water rights to a particular meter and the number of meters particular to a single water right, notifies the metering coordinators if a user has not submitted data for a particular year and also notifies metering coordinators when a report has been submitted and accepted, and prints or e-mails reminder letters at the beginning of each year reminding the users that the water use report is due if the user has not submitted a report.

Development is a continuing process, with enhancements added as needed. Constraints from lack of personnel to develop the database were a major problem, which was addressed by writing and signing a project management plan that identified constraints, risks, and roles and responsibilities. After the plan was accepted and signed, development then proceeded without further delay. The project management plan is basic to developing the database as it details what Ecology wants in and from the database, and provides the necessary focus.

The Fourth Challenge – Education

Two years into the program, problems with metering and reporting began to surface. It took that length of time because the second year was when most users were to begin reporting. The main difficulty with most was that users did not know how to read meters on pressurized systems. Ecology identified meter purveyors as a major conduit to address the problem. Another difficulty identified was the selection and installation of meters. Meters had been installed that were not capable of measuring minimum flows and with no thought given to straight pipe requirements. Training was identified as the method of correction.

Training sessions are held periodically to emphasize to meter installers the proper assessment of pressurized pipe systems to make sure the proper type of meter is installed, especially considering minimum rates of flow where most problems have occurred, and on the required amount of straight pipe before and after a meter. Another concern is the totalizer. Ecology recommends that meters be installed with totalizers that totalize in acre-feet rather than gallons if possible, or in the largest units in gallons possible. The training sessions with the purveyors and users appears to be working, as the reports submitted have fewer errors.

Education also is and will be addressed by direct discussion with individual users, public meetings, and agricultural organizations such as the Washington State Farm Bureau and conservation districts. Presenting the metering program to the Boards of Directors of conservation districts and at annual meetings is particularly effective. Ecology has entered into agreements with conservation districts to administer cost-share funds as well to foster cooperation and trust with water users, which also works well. The Conservation Districts also provide education to individual users on reading meters. The arrangement shortens the line of communications and enhances the metering program accordingly.

On open channel systems, there is a lack of technical expertise about open channel systems and the variety of methods available to measure water. Expertise is lacking in knowing how to assess a system and select a measuring device (weirs, flumes, submerged orifice, etc.) for a particular diversion. As well, the concept of designing a system for automation is not well understood. In those cases, Ecology provides direct assistance to the user and whoever may be installing a system, and uses the expertise of the Bureau of Reclamation as much as possible.

Emphasis is especially being placed on installation of data-loggers on open channel systems along with Supervisory Control and Data Acquisition (SCADA) equipment when appropriate. Fortunately, the choice of data-loggers and various types of equipment is broadening, and manufacturers and dealers are willing to try new approaches and develop turnkey systems applicable to many small, less that 10 cubic feet per second, diversions in order to reduce costs, simplify operation, and install more such systems.

<u>The Fifth Challenge – The Universe of Uses for the Data</u>

Identifying the universe of uses for the data has not been completed. At the least, it will be used for identifying overuse, illegal use, and non-use. Each of those areas alone presents difficulties as each involves enforcement and the application of the police powers of the state, precisely what water users' fear. However, there will be a number of other uses for the data, particularly in research involving in-stream flows, water balance studies, crop management, projecting use over time and into the future, impacts on changes in land use, water banking, and so forth. It is too early to yet identify the universe of uses, but it will begin as soon as interested parties have access to the aggregate data in a basin or basins. It is expected that interest will be particularly high in studies involving migration of salmonid fishes, efforts at recovery of endangered salmonids, community and economic development, and watershed management.

<u>The Sixth Challenge – The Columbia River Bill</u>

The Columbia River bill involves a major effort by Ecology to come to terms with the issue of whether or not there is water available for further appropriations. All parties interested in the water issues associated with the Columbia River are interested, to say the least. The effort will affect the Columbia River from the Canadian border to the Bonneville Dam on the Columbia River.

One aspect of the bill is to require metering on all surface water diversions from the Columbia River and all groundwater withdrawals within a one-mile corridor on both sides of the Columbia. The lessons learned over the last four years will serve Ecology well in accomplishing that effort. There will be a major educational effort with water users about this because it is apparent that most of the estimated 5,000 to 6,000 users in the corridor are not even aware that the bill was passed.

CONCLUSION

The metering program of Ecology is probably the most comprehensive metering and reporting program in the Western United States. There were a lot of lessons to be learned and many are yet to be learned. Expertise needs to improve, and education needs to proceed at a quick pace. One of the biggest lessons learned is that people have to be players in the game. They have to be brought into the process early, sought out for advice, listened to and heard, and trusted. Ecology has met the first, third, and fourth challenges and is working to improve on those challenges.

The second challenge, data collection and data quality, is being tested this year and will be resolved for 2007. The fifth challenge, the universe of uses for the data, is still in the wings waiting on data collection and quality. The sixth challenge, the Columbia River bill, starts this year and will build on the lessons learned from the last four years since the metering program was implemented in 2002. The second challenge, data collection and quality, will have to be resolved at the same time the Columbia River bill is implemented.

Overall, one has to conclude that water metering on the scale being implemented in the State of Washington uses social science skills as much as technical skills. For large operations such as Bureau of Reclamation projects and municipalities, implementation is largely accomplished by hiring the requisite technical skills. For implementation involved many independent users such as occurs in the State of Washington, skills in the social sciences are needed to achieve consistent, concrete, and reliable results that can accumulate necessary data for long-term use in research and adapting to the changing demands on water resources and infrastructure. Reasons are varied, and involve building trust, openness, development of interdisciplinary skills to resolve technical and social issues, understanding cultural values, politics and the making of policy, developing educational skills, and the like.

REFERENCES

Anderson, T.L., and P.S. Snyder: 1997, "Priming the Invisible Pump," *Property and Environmental Research Center Policy Series No. PS-9.*

Benjamin, D.K.: 2006, "Tangents: Environmental Reputation," *Property and Environmental Research Center Reports,* March, p. 19.

DuBos, R.: 1968, *So Human an Animal,* Charles Scribner's Sons, New York.

Harwood, K.: 2005, "The Evolution of Wet Growth Regulations: City of Santa Fe," *Water Resources Impact*, **7:6**, pp. 5-8.

Henrie, M.: 2005A, "Water as a Growth Tool – Introduction," *Water Resources Impact*, **7:6**, November, p. 4.

Henrie, M.: 2005B, "Oregon's Municipalities Can Take The Time They Need To Grow," *Water Resources Impact*, **7:6**, Nov, pp. 12-14.

Higbee, E.: 1957, *The American Oasis,* Alfred A. Knopf, Inc.

Levine, J.: 2004, *Adaptive management in river restoration: theory vs. practice in western North America,* Water Resources Center Archives. Restoration of Rivers and Streams, http://repositories.cdlib.org/wrca/restoration/levine.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier: 2005, "Declining Mountain Snowpack In Western North America," *American Meteorological Society*, 39 – 49.

Okonski, K.: 2006, "Montana: On the Verge of Collapse?" *Property and Environmental Research Center Policy Series No. PS-35*.

Saunderson, M.H.: 1950, *Western Land and Water Use*, University of Oklahoma Press, OK.

Shanks, B.: 1984, *This Land Is Your Land: The Struggle To Save America's Public Lands*, Sierra Club Books, San Francisco.

Smith, F., J. Taylor, R. Belzer, V. Porlier, and K. Green: 2002, "Why Did The Greens Win?" *Property and Environmental Research Center Reports,* **20:2**, 6-9.

Thabault, M.G.: 2005, "The Role of Science in Balancing the Needs of Protected Species: An Historical Perspective," *Journal of Contemporary Water Research and Education*, Issue No. 31, pp. 2-12, June.

Vaux, H., Jr.: 2005, "Water Resources Research in the 21st Century," *Journal of Contemporary Water Research and Education*, Issue 32, pp. 2-12, June.

__________: 2005, *Western States Water Newsletter*, Issue No. 1634, Sept. 12.

GILA RIVER INDIAN COMMUNITY WATER RESOURCES DECISION SUPPORT SYSTEM — A MODELING SYSTEM FOR MANAGING A MULTI-SOURCE CONJUNCTIVE USE WATER SUPPLY FOR LONG-TERM SUSTAINABILITY

Brian D. Westfall[1]
Andrew A. Keller[2]
Ronald D. Bliesner[3]
Tim Flynn[4]
Shane Lindstrom[5]

ABSTRACT

The Gila River water rights settlement will restore to the Gila River Indian Community (GRIC) a water supply necessary to meet present and future demands on their tribal homeland. The settlement provides water from nine water sources, including delivery from four irrigation districts, treated municipal effluent, irrigation return flow and supplemental groundwater. The Gila River Indian Community Water Resources Decision Support System (WRDSS) was developed to effectively manage this complex water supply and protect the underlying aquifer. The WRDSS consists of three model components: Overall Water Resource Analysis (OWRA); Interface Manager (IM); and the Ground Water Analysis (GWA).

The OWRA model component tracks water delivery and the salt load from a water source to any delivery point through a branching flow network. Water supply preferences and priorities can be specified for each user for each water source. Water is delivered based on supply preference when water is abundant and by priority when water is short. Seepage and evaporation losses in the delivery and drainage systems, deep percolation from agricultural nodes, and costs and returns are also computed by the OWRA. The OWRA is tied to the GWA via the Interface Manager.

The Interface Manager is the tool used to convert output from the OWRA to a format that is compatible with the input requirements of the GWA. The OWRA estimates deep percolation and seepage from the conveyance network and irrigated areas. The IF spatially maps these groundwater recharge inputs to the

[1] Senior Project Engineer, Keller-Bliesner Engineering, LLC, Logan, Utah
[2] Vice-President, Keller-Bliesner Engineering, LLC, Logan, Utah
[3] President, Keller-Bliesner Engineering, LLC, Logan, Utah
[4] President, Aspect Consulting, LLC, Bainbridge Island, Washington
[5] PMIP Water Management Engineering, Sacaton, Arizona

grid cell network used in the GWA model. Any groundwater demand expressed by the OWRA is also specified as an input to the GWA on an established time-step.

The Ground Water Analysis component is a modeling tool based on MODFLOW (MacDonald and Harbaugh, 1988), to simulate surface/groundwater interactions and groundwater flow conditions, and MT3D (Zheng, 1990) to evaluate changes in groundwater quality over time. The GWA is used to evaluate the groundwater demand, in terms of yield and water quality, specified by the OWRA. As the groundwater demand changes so do the economics of pumping and water quality. This requires iterations between the OWRA and the GWA.

INTRODUCTION

Central Arizona Project Settlement Act

The Gila River Indian Community (GRIC) Water Rights Settlement was authorized by Title II of the Arizona Water Settlements Act (S. 437), also referred to as the Central Arizona Project Settlement Act of 2003. The settlement is the result of 13 years of negotiation between 35 parties, including the Gila River Indian Community (Community), the Federal Government, and various water users in the Gila River basin. Under the agreement, the Gila River Indian Community will receive a permanent entitlement to 653,500 acre-feet of water per year. This water supply is intended to meet the municipal, residential, industrial, recreational and commercial water requirements of the Community and supply irrigation water to approximately 146,000 acres of crop land. As a part of the settlement, funding is provided to enhance the water delivery system, to connect the various sources, and deliver water to all 146,000 acres of agricultural lands.

Water Supply

Nine water sources are identified in the settlement agreement representing water rights to 653,500 acre-feet per year. Since flow from some sources is highly variable, ground water is used to balance the supply. The sources also vary in water quality and cost, and some have associated storage while others are direct flow. They enter the reservation at several locations shown on Figure 1. Table 1 describes the sources of water identified in the settlement and the quality of each source. This high variability in water sources leads to challenging water management, especially when coupled with the requirement of delivering water to municipal, residential, industrial, environmental, recreational and agricultural uses while managing water and salt levels in the aquifer. A quick review of Figure 1 points out the complexity of the water balance problem.

Water Resources Decision Support System

The Water Resources Decision Support System (WRDSS) was developed as part of the Gila River Indian Community Comprehensive Water Management Plan (Keller-Bliesner Engineering, et al, 2001) to effectively manage this complex water supply and protect the aquifer. The WRDSS consists of three model components: Overall Water Resource Analysis (OWRA); Interface Manager (IF); and the Ground Water Analysis (GWA).

The WRDSS is a management and planning tool to help answer questions such as:

- What is the sustainable size of the irrigated area?
- How should poorer quality water be used?
- How should groundwater resources be used and developed?
- What is the potential for groundwater recharge?
- How do various scenarios affect the economics of the project?

The focus of this paper is the OWRA and the Interface Manager (IM). The GWA will be mentioned briefly but the reader is referred to the paper by Flynn et al., (2006), included in these proceedings.

Table 1. P-MIP Water Source Descriptions

Water Source	Description	TDS – mg/l
San Carlos Indian Irrigation Project	**Existing water supply with both direct flow and storage water. Highly variable supply.**	**Mean - 785**
Central Arizona Project (CAP)	Decreasing supply with time as upper basin develops.	Mean - 550
Salt River Project	Deliverable at up to 6 locations. Has some storage, but at lower priority.	Mean - 734
Chandler Exchange*	Delivered as produced with no storage. Some blending required.	Mean – 1,200
Mesa Exchange*	Same as Chandler Exchange except different delivery location.	Mean – 1,200
Haggard Decree	Limited to west side only. Delivered as return flow from SRP supplemented with groundwater.	Drain – 1,060 Well – 2,480
R.W.C.D **	Delivered through the RWCD Canal.	Mean - 734
Drains	Non-regulated return flow entering the reservation. Expected TDS about 775 mg/l.	Mean - 775
Ground Water Wells	Existing and new wells on reservation. Used supplemental to surface supply. Widely varying annual diversion. TDS will change with time from irrigation losses and recharge from flows in the Gila and Santa Cruz Rivers.	Current range 550 – 3,600

* Reclaimed water from Chandler and Mesa is received at no cost in exchange for their use of Community CAP water. Delivery is 1.25 times the CAP water.
** Roosevelt Water Conservancy District.

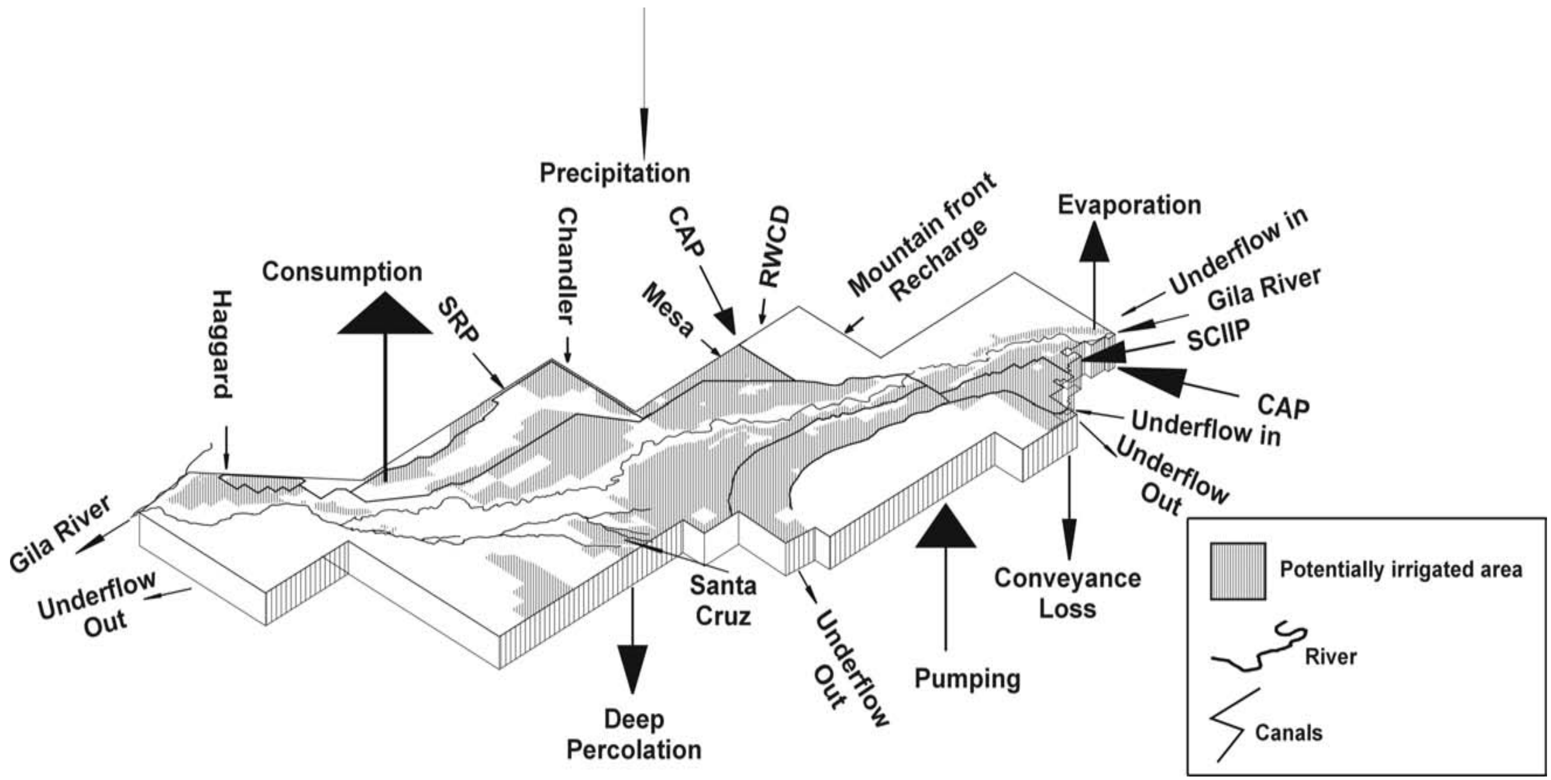

Figure 1. Water Balance Schematic for the Gila River Indian Reservation Showing Water Sources.

OWRA

Overall Water Resources Analysis Description

The OWRA is a surface water planning model designed to run on Windows based PCs. It has been successfully tested on both Windows 2000 and Windows XP operating systems. The software is written in Microsoft Visual Basic.Net and uses a web based deployment technology. This gives the user the option of updating to the most current version automatically if one is available.

As currently designed, the OWRA simulates surface water and salt flow and associated costs though a river basin on a monthly time step. It models water and salt flow from sources to demands through a branching node network. A model is built through a graphical user interface by dragging simulation objects or nodes from either an object tree or pallet to the model workspace. These objects represent features found in a typical basin. The OWRA has the following node types:

Demand Nodes
- Agricultural
- Municipal and Industrial
- Recharge or Wetland

Source Nodes
- Source
- Reservoir
- Well Field

Reach Nodes
- Reach
- Diversion

Utility Nodes

Connections between nodes define flow paths along which water can be allocated during a simulation. Such connections are made by simply dragging a link from one object to another. One end of the link has an arrow and shows the direction of water flow. A section of an example model is shown in Figure 2.

Each object has a set of properties specific to the physical characteristics of the node. Figure 2 shows an example property window for an agricultural demand node object. The node is configured on the “Basic Information” tab. The “Memo” tab contains a mini word processor that may be used for documentation. The “Output” tab contains pertinent model simulation data for the node. Simulation data are only available after a model run has been completed.

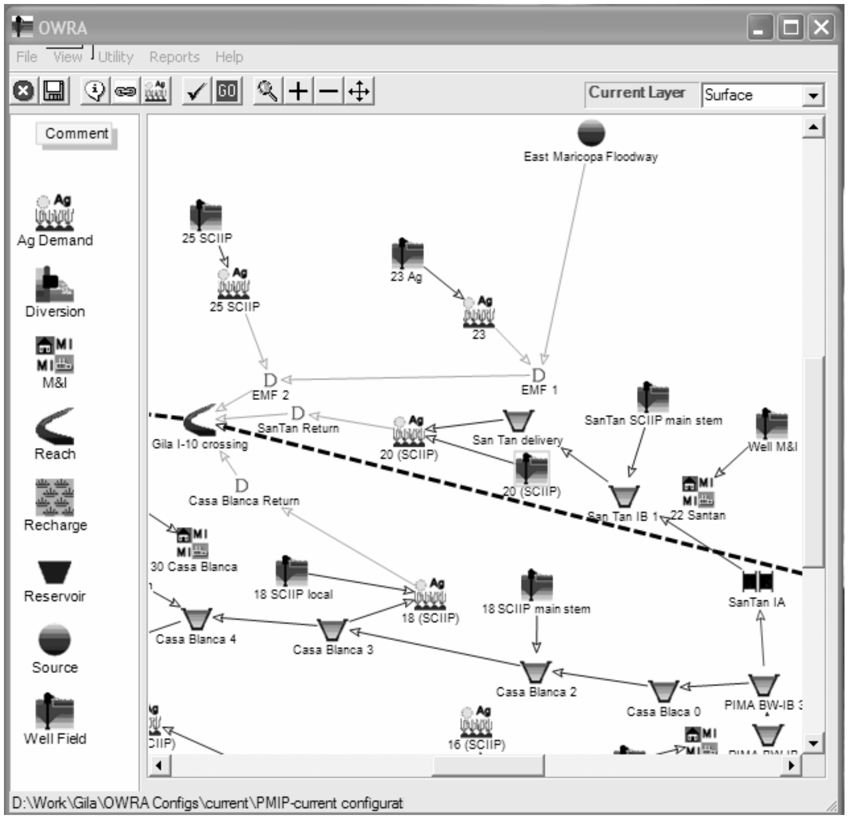

Figure 2. Screen capture of the OWRA with a typical model.

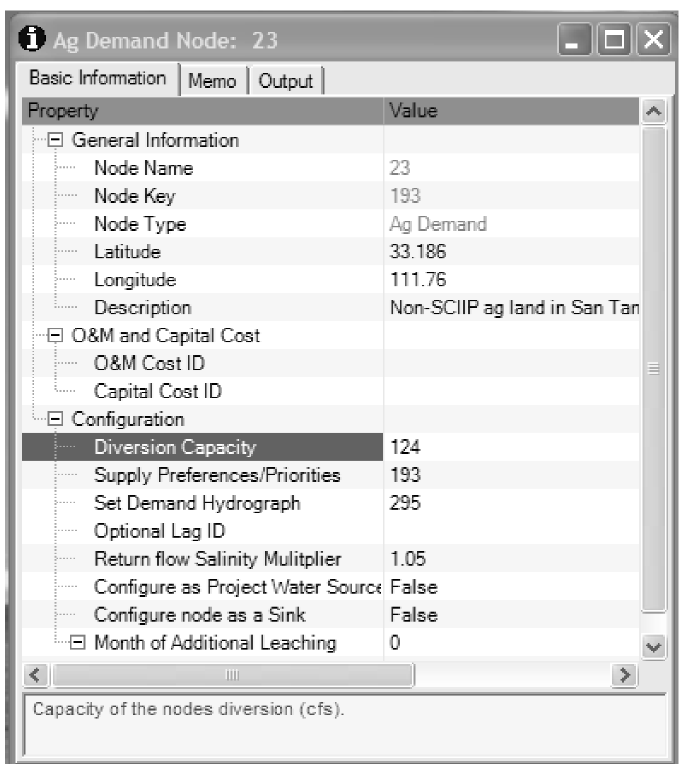

Figure 3. Agricultural Demand Property Window.

Source Preferences and Priorities

The user specifies what water sources may be used by each demand node. The list of sources is ranked by preference and by priority. A water user may prefer water from a particular source due to quality or cost considerations but may have a junior right. During simulation an attempt is made to allocate water by preference. If this fails due to inadequate supply, then water is allocated by priority.

The model tracks the volume of water and associated salt along any flow path from the source to the demand. Each flow path is tracked independently. The difference between the volume of water allocated at the source and the volume of water delivered to the demand are the intervening reach seepage and evaporation losses. The use of individual flow paths makes it possible to track the "color" of water delivered to every demand node. The concept of flow paths is discussed further in the next section.

Flow Paths

In the OWRA, flow paths are physical pathways that water follows from a source node to a demand node. Every model configuration must have at least one flow path. Complex networks may have hundreds of nodes and thousands of flow paths. Flow paths are defined implicitly by the arrangement and connection of individual nodes in the network, as configured by the user. The OWRA automatically identifies each feasible flow path at the start of a simulation by building a detailed list of unique paths. Conveyance loss coefficients, consisting of evaporation and seepage, are determined for each flow path as the list is constructed. During simulation the volume of water that must be released from a supply node to satisfy the water requirement at a specific downstream demand node is determined, subject to all physical limitations such as reach and structure capacities and losses along the flow paths.

Administrative losses, or spills, at the ends of canal branches, are not considered in the model. This is because the model calculates water allocations, not actual system operations, which involve complex decisions to deal with unanticipated events such as sudden rainstorms, emergency maintenance needs, unforeseen changes in water demands, and others. However, if an operational spill is consistent and known, it can be specified as a non-consumptive demand in the model.

Demands

The OWRA simulates water demands and uses for three types of demand nodes: irrigated agriculture, municipal and industrial, and recharge and wetlands. Agricultural demand nodes are the most complex and are specified according to the crop mix and acreage, which can vary with time, and the associated consumptive irrigation requirement. For each crop in the mix the irrigation system mix is defined along with the associated tail water and deep percolation fractions of the delivered water. Salt balance is maintained within the crop tolerance by determining the leaching requirement for each crop and irrigation method combination. Leaching requirements that are not satisfied during the crop season are specified by dedicated leaching events. The capital and operation and maintenance costs associated with irrigation are combined with the net crop return, which is adjusted for water shortage and salinity, to compute the return to land and water.

Municipal and industrial demands are specified as time varying series with lagged return flow fractions. Recharge basins and wetlands are treated as infiltration basins with specified seepage and time varying evaporation losses.

OWRA Simulation Results

Monthly output data from the OWRA simulations are saved to a Microsoft Access database for processing by the Interface Manager (IM). Data saved for each node depends on the node type. Since the primary purpose of the OWRA is to simulate long term planning level operation of the PMIP irrigation project and its affect on the underlying aquifer, the associated groundwater pumping and recharge through deep percolation including their salt concentrations are key output data.

INTERFACE MANAGER

The Interface Manager is a separate application that has two major functions. The first is to convert the recharge and pumping data simulated by the OWRA into a format that is compatible with the GWA. The second is to convert pumping data from the GWA into a format compatible with the OWRA.

When processing OWRA output to create GWA input, the IM reads the OWRA output database and produces two primary tables. These are a recharge table and a pumping table. Monthly seepage and deep percolation from OWRA nodes are tabulated along with the salinity in the recharge table. The water allocated monthly from each well field node, initial pumping depth and salinity are compiled in the pumping table.

The GWA is based on a MODFLOW groundwater model developed by Aspect Consulting (Flynn et al., 2006). From a two dimensional perspective (x and y dimensions) the groundwater model uses 4664 800 m x 800 m (0.5 mile x 0.5 mile) grid cells to represent the GRIC model domain. Using GIS, the OWRA node boundaries were overlaid on the groundwater grid cells to produce a factor that represents the proportion of an OWRA node that overlays a particular groundwater cell. This is referred to as a cell node deep percolation factor. Each

OWRA node that intersects a groundwater grid cell has a cell node deep percolation factor. It is possible for a single groundwater grid cell to receive recharge from multiple OWRA nodes. For linear features such as stream and canal reaches, each grid cell that a reach crosses is given a factor representing the portion of the reach that crosses the cell.

The recharge for each grid cell is calculated by the IM by summing the product of the associated cell node deep percolation factors times the deep percolation or seepage volumes for the overlaying nodes. The recharge salinity is a weighted average of the deep percolation and or seepage from each node.

The IM produces a 3-dimensional plot showing the average annual recharge by groundwater cell as shown in Figure 4. The IM also writes two text files, one for recharge and one for pumping that are read by the GWA.

When the IM is using GWA output to create OWRA input, pumping data are read from an output file created by the GWA and written back to the OWRA database. In the first iteration, well field capacities, pumping depths and salinities were assumed by the OWRA based on initial groundwater conditions. As stress is put on the groundwater aquifer due to pumping, all three of these variables may change. If the variables change more than a user adjustable tolerance, then another OWRA – GWA iteration is completed. This iterative process continues until the change in the modeled groundwater data is less than the set tolerance.

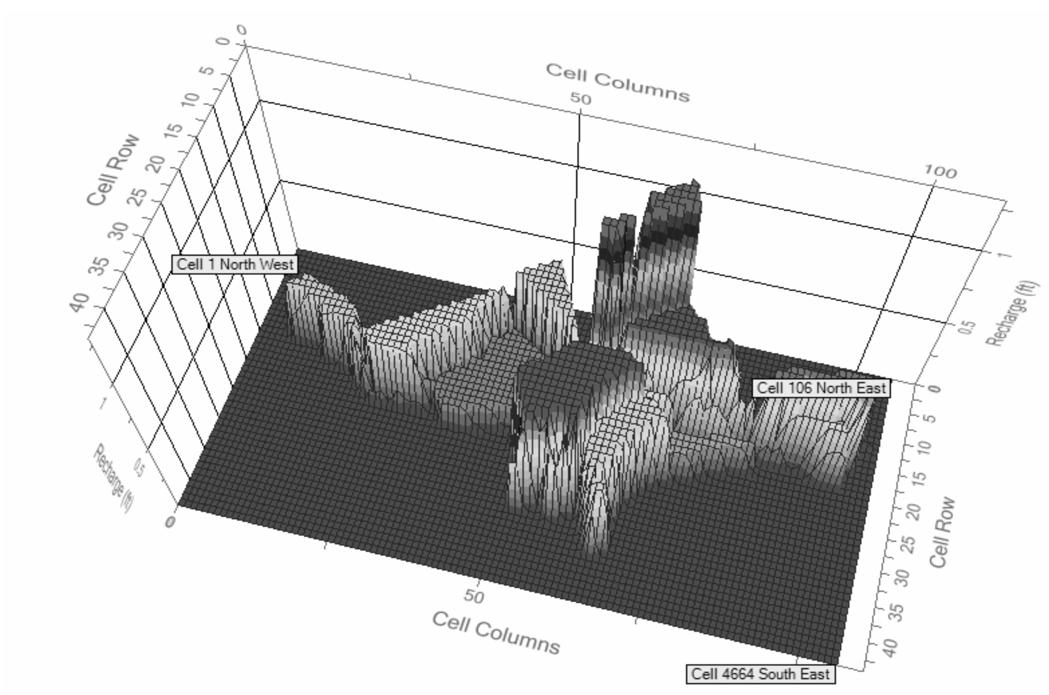

Figure 4. Interface Manager Plot of Average Annual Recharge by Groundwater Grid Cell.

CONCLUSION

The OWRA, IM and the GWA are three components that make up the Gila River Indian Community Water Resources Decision Support System (WRDSS). The WRDSS is a key tool to be used by GRIC in developing, managing and protecting its surface and groundwater resources. WRDSS has the flexibility and comprehensiveness necessary to evaluate the complex and varied interactions among multiple water sources and uses within GRIC to assure long-term sustainability of the land and water resources.

REFERENCES

1. Keller-Bliesner Engineering, LLC., Aspect Consultants, LLC., Northwest Economic Associates, Inc., 2001. Gila River Indian Community Draft Comprehensive Water Management Plan.

2. MacDonald M.G. and A.W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground Water Flow Model. Techniques of Water-Resources Investigations of the United States Geological Survey. Book 6, Chapter A-1.

3. Zheng, C., 1990 MT3D: A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Ground water Systems.

4. Flynn, T.J., Bannister P.S, Bliesner, R.D., Keller, A.A., Lindstrom, S., 2006, Groundwater Analysis Tool: A Component of the Water Resources Decision Support System for the Gila River Indian Community, 2006 USCID Water Management Conference.

GROUNDWATER ANALYSIS TOOL: A COMPONENT OF THE WATER RESOURCES DECISION SUPPORT SYSTEM FOR THE GILA RIVER INDIAN COMMUNITY

Timothy J. Flynn[1]
Peter S. Bannister[2]
Ronald D. Bliesner[3]
Andy A. Keller[4]
Shane Lindstrom[5]

ABSTRACT

The Gila River Indian Community's Water Resources Decision Support System (WRDSS) provides an operations and planning tool for managing a multi-source water supply to sustain the Community in their tribal homeland. The Gila River Indian Community Water Right Settlement Act of 2003 provides water from nine sources, including imported surface water supplemented with groundwater. These sources are needed to meet multiple water supply needs including agricultural use by the Gila River Indian Community. The expansion of irrigated agriculture, importation of surface water, and increased groundwater withdrawal within the Reservation will change the long-term groundwater balance – in terms of both quantity and quality. Managing and protecting the groundwater resource for multiple purposes within the framework of the Community's water resource management goals, objectives, and economic constraints is a key component for long-term water supply sustainability.

The Groundwater Analysis (GWA) is one of three components of the WRDSS. It is linked to an Overall Water Resources Analysis (OWRA) module, which manages the conjunctive use of surface water and groundwater supplies, via an Interface Manager (IM) component. The GWA is a modeling tool based on an analytical model for unsaturated flow and salt transport in the vadose zone, the numerical groundwater flow model (MODFLOW), and a numerical solute transport model (MT3D) for salt transport in groundwater. The GWA is used to evaluate aquifer yield and water quality constraints in response to meeting water supply demand specified by the OWRA. It also provides a management tool to forecast potential impacts and assess management strategies for long term sustainability of the groundwater resource.

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[1] President, Aspect Consulting, LLC, Bainbridge Island, Washington
[2] Project Engineer, Aspect Consulting, LLC, Bainbridge Island, Washington
[3] President, Keller-Bliesner Engineering, LLC, Logan, Utah
[4] Vice President, Keller-Bliesner Engineering, LLC, Logan, Utah
[5] Pima-Maricopa Irrigation Project Engineering, Sacaton, Arizona

INTRODUCTION

A water resources management plan was developed to manage the conjunctive use and long term sustainability of surface water and groundwater resources available to the Gila River Indian Community (GRIC). The Central Arizona Project Settlement Act entitles the GRIC to 653,500 acre-feet of water per year to meet agricultural and non-agricultural (municipal, industrial, environmental, and recreational) water supply needs into the future. This quantity will be provided by a combination of imported surface water sources and groundwater withdrawal on the Reservation to cover any annual shortfalls. Meeting the objectives of the GRIC, including irrigation supply to approximately 146,000 acres of crop land, will require careful development and management of the Reservation's groundwater resource.

A water resource planning tool, referred to as the Water Resources Decision Support System (WRDSS, Bliesner et. al., 2004), provides a framework for both operational (short-term) and strategic (long-term) water supply analyses. The WRDSS integrates the various water sources, water demands, and associated economics by interfacing separate surface water and groundwater model components that address both water quantity and quality. The WRDSS consists of three model components: Overall Water Resources Analysis (OWRA); Interface Manager (IM); and the Groundwater Analysis (GWA). This paper discusses the design and function of the groundwater analysis (GWA) and how it relates to the other WRDSS components. The OWRA and IM are described in an accompanying paper by Westfall et. al., 2006, included in these proceedings.

GROUNDWATER ANALYSIS (GWA) COMPONENT

GWA Elements

The GWA is a modeling tool designed to evaluate the effects of pumping and irrigation on the groundwater quality and quantity. The GWA model is based on a detailed assessment of hydrogeologic and water quality conditions within and surrounding the Reservation. This hydrogeologic assessment was a key first step in developing a predictive model representative of the physical system. The GWA consists of three principal elements that together "represent" the physical system:

1. An analytical model describes unsaturated flow and salt transport in the vadose zone (unsaturated zone above the water table);
2. A numerical hydraulic model (MODFLOW) describes saturated groundwater flow; and,
3. A numerical mass transport model (MT3D) describes salt movement in the saturated zone.

A schematic of the GWA elements, general linkage, and flow of information, including the exchange of model inputs and outputs with the OWRA, is presented in Figure 1. The GWA is supported by a groundwater database, developed in Microsoft Access, which serves as a repository for historical, baseline, and future hydraulic and water quality data. The groundwater database will also store all input and output data related to predictive model runs, as an integral part of the modeling tool. The primary inputs from OWRA include recharge, and associated salt (total dissolved solids) concentration. For a water supply demand simulation, the OWRA also specifies a groundwater quantity and water quality requirement to meet that demand. GWA output to the OWRA is pumping lift (cost) and water quality of the groundwater supply based on the well configuration selected to meet the specified demand.

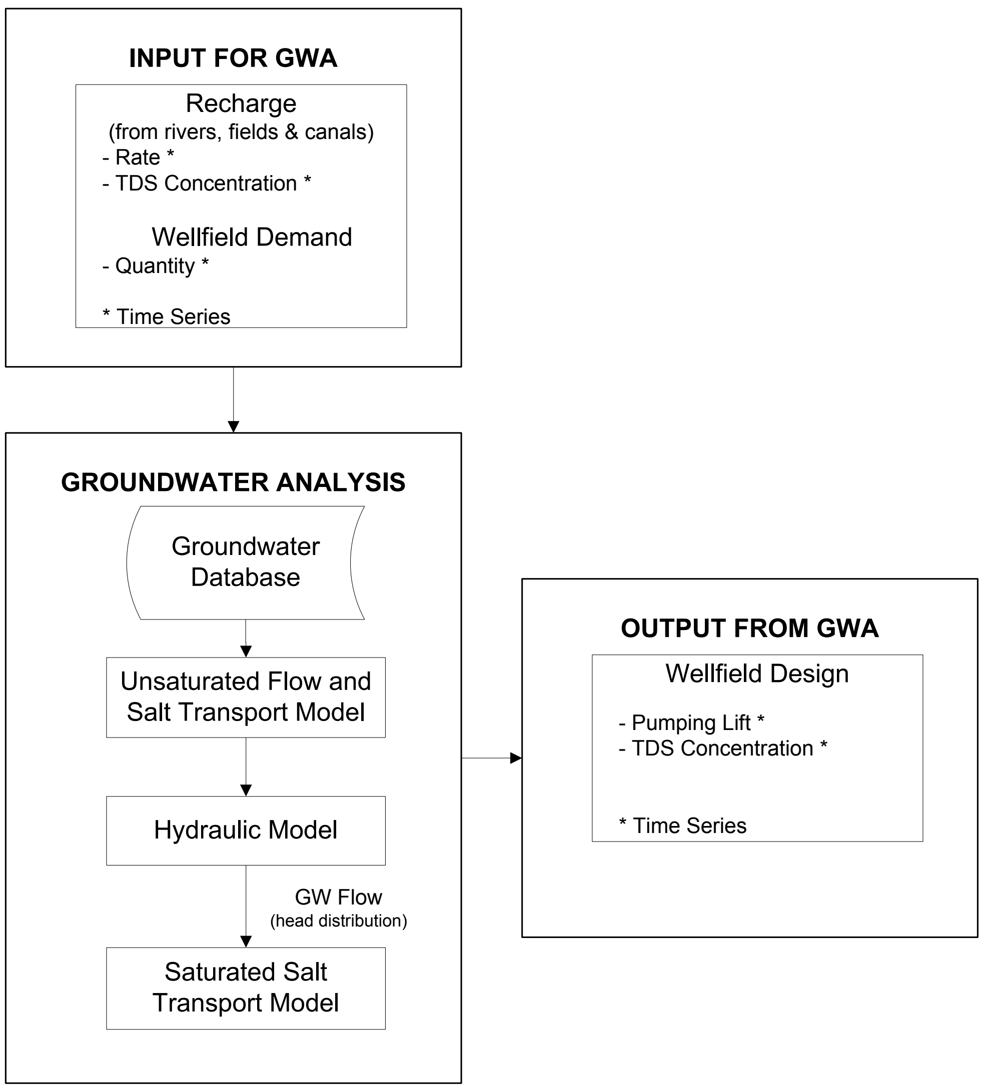

Figure 1. GWA Model Elements

Unsaturated Flow and Salt Transport: The GWA uses an analytical approach to compute the time-lag for irrigation water and associated dissolved salts, which are applied at the ground surface, to reach the groundwater table. This time-lag calculation is computed outside of the numerical MODFLOW model utilizing an analytical "spreadsheet" model which is easily and directly incorporated into the GWA.

The analytical approach is based on the advection dispersion equation (e.g., Hillel, 1998) to estimate the time-lag for salt breakthrough at the water table in response to irrigation return flow below the root zone. Groundwater flow in the unsaturated zone is governed by Darcy's law, with hydraulic conductivity and hydraulic head expressed as functions of moisture content. Salt transport in the unsaturated zone is governed by the advection dispersion equation, with groundwater velocity and dispersion coefficients also expressed as functions of moisture content. The van Genuchten equation (Tindall and Kunkel, 1999), which is widely used in agricultural applications, is used to describe the relationship between soil moisture content and hydraulic conductivity.

Input parameter requirements for computing the vertical salt movement in the unsaturated zone with respect to depth and time include: the average irrigation return flow, saturated hydraulic conductivity (vadose zone), depth to groundwater, salt concentration in the return flow (below the root zone), soil dispersivity, and soil characteristic curves to describe the relationship between moisture content and hydraulic conductivity.

Recharge is input into the groundwater flow model, likewise, the salt concentrations computed using this analytical method are input as a source term into the saturated salt transport model, described below. The hydraulic time lag (e.g., recharge of irrigation return flow) will approach zero as "piston" flow develops, however the salt time lag remains a function of depth to the groundwater table.

Saturated Flow: The groundwater flow model was developed using the numerical code MODFLOW (Harbaugh, et. al. 1996), an industry standard for modeling groundwater flow in saturated porous media. MODFLOW is used as a predictive tool to forecast and evaluate aquifer response to varying water resource management demands and conditions, at multiple spatial and temporal scales (e.g., pumping induced well field response versus long-term changes in groundwater conditions across the Reservation). Groundwater Vistas™ (Environmental Simulations, Inc., 2004) was used as a graphic interface to facilitate model input, output, sensitivity analysis, and calibration.

The "footprint" of the flow model extends beyond the Reservation boundary to incorporate the influence of off-reservation pumping and to address natural hydrogeologic boundaries. The total area included in the flow model is over 2000 square miles. The model is constructed by subdividing the area into a horizontal grid (1 square mile cells) with vertical layers, based on the principal hydrostratigraphic units encountered on the Reservation. To facilitate local scale analysis, the hydrostratigraphic units were further subdivided into a total of eight vertical layers to provide improved flow simulation of pumping effects, aquifer characteristics, and vertical hydraulic gradients. The level of vertical layer discretization is also critical in evaluating water quality changes associated with salt loading using the solute transport analysis, discussed below. MODFLOW performs water balance calculations on each of the “blocks” based on head changes imposed by stresses placed on the groundwater system (e.g. recharge or well pumping).

The flow model outputs head values for each cell. Pumping levels at wellfields are further evaluated in a spreadsheet outside of MODFLOW using the analytical Thiem correction (Anderson and Woessner, 1992). MODFLOW calculates the groundwater level across an entire grid cell, which underestimates pumping lift because of spatial averaging. The correction is applied to provide a more accurate determination of pumping lift for output to the OWRA. The amount of correction is related to the size of the cell, the type of aquifer material, and the pumping rate.

Salt Transport in the Saturated Zone: In addition to evaluating groundwater flow, the GWA is designed to track the accumulation of salts, evaluate changes in groundwater quality on the Reservation, and predict the water quality of groundwater supply from on-Reservation wells. Salt transport within the saturated zone is evaluated using the numerical solute transport model MT3D (Zheng, 1990) with flow conditions specified by output from MODFLOW. The output from MODFLOW includes a groundwater head (equipotential) file, a cell-by-cell flow file specifying volumetric inputs and outputs for each cell, and an input file for MT3D.

Understanding the vertical movement of salt and resultant water quality impact in the aquifer system, is critically important in assessing the long term sustainability of the Reservations groundwater resource. The flow model was designed with eight vertical layers to facilitate tracking the movement of salt through the aquifer system. The transport simulation generally uses average or steady-state groundwater velocities to reduce the computational timeframe, however transport simulations can also be made for transient groundwater flow conditions.

Design Flexibility to Address Multiple Spatial and Temporal Scales

A key attribute of the GWA is the flexibility to address groundwater quantity and quality issues at multiple spatial and temporal scales. The WRDSS was developed to provide a tool to evaluate both operational (e.g. forecasting the quantity and quality of a well field supply to meet irrigation demand) as well as the strategic planning (e.g. assess sustainable groundwater yield and storage across the Reservation) objectives of the GRIC. To provide this functionality, the GWA uses a model grid scaling tool to provide improved resolution to support both flow and salt transport simulations at multiple spatial scales while preserving a reasonable simulation run time. GWA simulations can also be run using different computational timesteps, to address varying time scales.

Variable Spatial Scale: The regional flow model employs a grid cell size of 640 acres, and covers an area approximately 4 times the size of the Reservation. The extent of the regional model was based on lateral model boundaries largely defined by 'no-flow' bedrock contacts. The regional model was adapted for more local scale analysis (e.g. at the Reservation-scale and wellfield-scale) using Telescopic Mesh Refinement, or 'TMR.' The graphical user interface for the numerical modeling, Groundwater Vistas™ , largely automates TMR, including processing the results of the larger hydraulic model to set the smaller hydraulic model boundary conditions. TMR is first employed for Reservation-scale analysis using grid cells of 160 acres in size. TMR is also employed using the results of the Reservation-scale model for more detailed analysis to simulate a particular wellfield-scale with 40-acre or smaller grid cells.

The TMR methodology is also used to minimize computational errors typically encountered in groundwater transport simulations, particularly in error-prone regions such as in the vicinity of sharp salt concentration fronts. High resolution subgrids are used to focus the evaluation of salt transport specifically within the boundaries of the Reservation or to describe transport in the immediate vicinity of specific irrigation areas or well fields. To avoid long model run times, the spatial extent of the model must be reduced along with the grid cell size.

Variable Temporal Scale: For operational planning (e.g. irrigation scheduling), monthly timesteps are required to identify problems associated with meeting the demand with acceptable water quality and pumping lift. Irrigation forecasting, using model runs with monthly timesteps, may extend over 5 to 10 year planning horizon.

For strategic planning, evaluating resource management issues such as changes in aquifer storage and cumulative salt loading requires analysis over longer timeframes and consideration of both on- and off-Reservation impact to groundwater. To facilitate strategic planning of groundwater resource use, longer timesteps can be used. For instance, periods of steady groundwater development (from 1900 to 1975) were simulated with 40-year, 10-year, and 5-year timesteps. On the other hand, the period 1975 to 2002 was characterized by a period of relatively frequent episodic flooding events. These conditions were simulated using annual and monthly timesteps to more accurately represent changes in recharge conditions.

Functionality and Linkage to OWRA

A flowchart showing the GWA model operation and linkage to the OWRA is illustrated in Figure 2. At the beginning of an analysis run, an initial set of conditions and objectives/constraints is established by the OWRA. For example, water management objectives may include determining the optimum number of irrigated acres based on available surface water sources and sustainable groundwater pumping (quantity and quality). Related analysis may include assessing water costs, optimizing well field design, or enhancing aquifer storage. With initial conditions and objectives set, the OWRA provides the quantity and quality of recharge throughout the groundwater model domain and specifies groundwater pumping demand and associated water quality requirements by area (e.g. irrigation zone). Well field configurations are identified and the GWA run to assess feasibility and define a range of operating conditions. Intervening scenarios can then be extrapolated from the range of GWA results, thereby reducing the number of model iterations.

The first step in the GWA process is evaluating the time lag for recharge to percolate to the uppermost aquifer. MODFLOW is initiated after recharge from the first irrigation event reaches the groundwater table. If results indicate that the demand cannot be met with the initial well configuration, then well locations and pumping rates will be optimized until demand is met, or if not feasible, an alternative water demand is specified by the OWRA and the GWA iteration is repeated.

Once the demand is met, then the modeling process advances to predict water quality using MT3D. If MT3D output indicates salt concentrations in the groundwater discharge meets water quality criteria specified in the OWRA, then the model output will be exported back to the OWRA (via the IM) and the results stored in the groundwater database.

If MT3D output indicates that the groundwater will exceed water quality criteria specified in the OWRA, an optimization step will be performed for well locations and pumping rates within the GWA. The optimization loop will be performed until model results are acceptable or the demand, as specified, is deemed infeasible. In this case, alternate demand or salt criteria would be input into the OWRA and the GWA rerun.

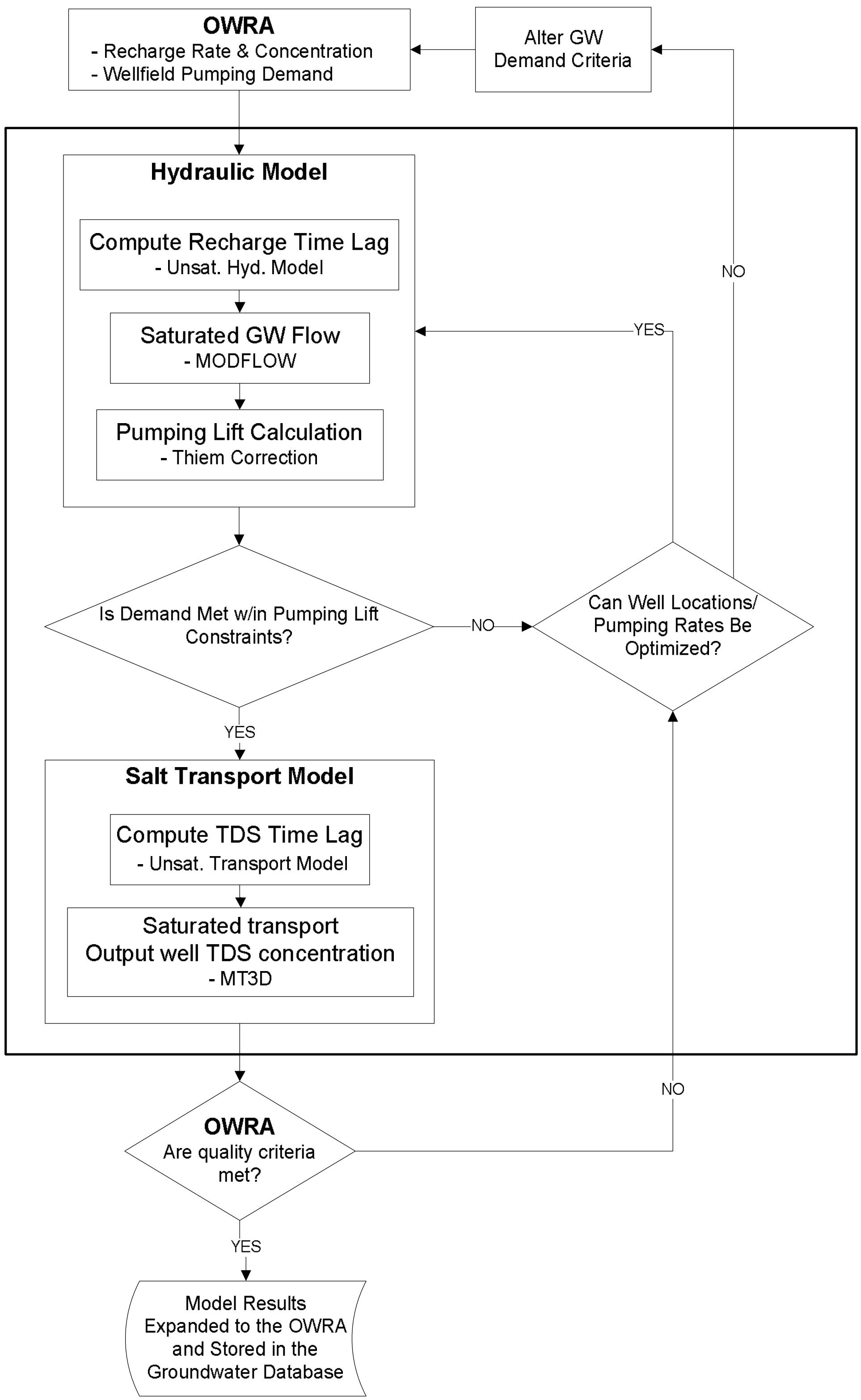

Figure 2. Iteration Sequence

SUMMARY

The GWA provides a modeling tool for evaluating changes in groundwater quantity and quality within the framework of the Gila River Indian Community Water Resources Decision Support System (WRDSS). A detailed assessment of hydrogeologic conditions within and surrounding the Reservation formed the conceptual framework for constructing the groundwater flow model. The GWA incorporates design flexibility to allow analysis at multiple spatial and temporal scales, to support the water resource management objectives of the GRIC.

ACKNOWLEDGEMENTS

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REFERENCES

Anderson, M. P. and Woessner, W.W., 1992, Applied groundwater modeling: simulation of flow and advective transport. San Diego, California: Academic Press, Inc.

Bliesner, R.D., Keller, A.A., Flynn, T.J., DeGrande, V., Sinclair, L., 2004, Gila River Indian Community – Managing a multi-source conjunctive use water supply for long-term sustainability, *in* Proceedings, Water Rights and Related Water Supply Issues, - Water Management Conference, p. 485-496.

Environmental Simulations, Inc. (ESI), 2004, Guide to using groundwater vistas, version 4.0.

Harbaugh, A. W. and McDonald, M. G., 1996, User's Documentation for MODFLOW-96, an update to the U. S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. U.S. Geological Survey. Open-File Report 96-485.

Hillel, D., 1998, Environmental Soil Physics: Fundamentals, applications, and environmental considerations, Academic Press.

Tindall, J.A. and Kunkel, J.R., 1999, Unsaturated zone hydrology for scientists and engineers, Prentice Hall.

Westfall, B.D., Keller, A.A., Bliesner, R.D., Flynn, T.J., Linstrom, S., 2006, Gila River Indian Community Water Resources Decision Support System – A Modeling System for Managing a Muli-Source Conjunctive Use Water Supply for Long-Term Sustainability, 2006 USCID Water Management Conference.

Zheng, C., 1990. MT3D: A modular three-dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems, Report to the USEPA, 170 pp.

GROUND-WATER BANKING IN THE EASTERN SNAKE PLAIN AQUIFER

Bryce A. Contor[1]
R.D. Schmidt[2]

ABSTRACT

All societies must make resource allocation decisions, assigning resources to the production of goods and services. Decisions must be made regarding how to utilize resources in production, what to produce, how much to produce, for whom to produce, and how to pay the factors of production (Medema, 1993). In Idaho and much of the western United States, the prior appropriation doctrine has been selected as the mechanism to allocate water. Most other resources are allocated by the market system, and some market mechanisms operate within prior appropriation.

Water banking is a tool that may expand the operation of market mechanisms within prior appropriation, helping to address current problems of conflict, waste, environmental harm and impeded economic growth. In other words, banking can be helpful in allocating scare water resources to the maximum benefit of society as a whole. In order to consider the possibility that a ground-water banking system in Idaho's Eastern Snake Plain Aquifer could improve efficiency, reduce conflict and supply water to ecological needs while protecting existing uses, the US Bureau of Reclamation (Reclamation) has funded a ground-water banking study with the Idaho Water Resources Research Institute (IWRRI). This is an investigative study designed to identify and explore issues, rather than to actually propose or construct a ground-water banking system.

Work to date suggests that instances of conflict, waste, ecological harm or impeded economic development associated with water use can be traced back to a deficiency in one or more market or property-right requirements. This premise is explored by considering hydrologic, economic and administrative considerations of externalities, and by considering public-goods characteristics of instream-flows for recreational and ecological purposes.

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[1] Research Hydrologist, Idaho Water Resources Research Institute, 1776 Science Center Drive Suite 305, Idaho Falls ID 83402. 208 282 7846, bcontor@if.uidaho.edu

[2] Groundwater Hydrologist, US Bureau of Reclamation, Pacific Northwest Region, 1150 N. Curtis Rd., Boise ID 83706. 208 378 5081, RSCHMIDT@pn.usbr.gov

BACKGROUND

Eastern Snake Plain Aquifer/River Interaction

Physical Description. The Eastern Snake Plain Aquifer occupies approximately 10,000 square miles in the southeastern part of the state, extending from Ashton, Idaho in the northeast to King Hill, Idaho in the southwest. The largest source of recharge is percolation incident to irrigation from the Snake River. The primary discharge is to the Snake River, via tributary springs and direct river gains. Ground-water pumping for agricultural irrigation is a large secondary discharge from the aquifer. The average net discharge from the aquifer to the Snake River is approximately 5,350,000 acre feet/year (Cosgrove et al, 2005). Especially in the summer months, the bulk of the flow in the Snake River at King Hill is derived from spring discharges. The Snake River is an important tributary to the Columbia River and an important migratory pathway for Pacific steelhead and salmon. In the vicinity of the springs, the Snake River is also habitat for sturgeon.

Administrative Concerns. Idaho's surface-water allocation process and ground-water allocation process were developed on parallel tracks that failed to acknowledge the hydraulic connections that can exist between surface water and ground water. In 1993, this failure was challenged by a user who relied on spring discharges and held senior water rights (Raines, 2004). One result of this challenge, known as the "Musser Case," was the implementation of conjunctive management rules for the Eastern Snake Plain Aquifer (Idaho Department of Administration, 1994). The rules officially link ground-water and surface-water administration, wherever a hydrologic connection exists. Idaho's implementation of the rules is evolving, with implications extending to ground-water transfers (Johnson et al, 2004) and surface-water delivery calls (Idaho Department of Water Resources, 2006).

Environmental Concerns - Mid-Snake. Summer-time water-quality concerns in the reach immediately adjacent to the springs include temperature, dissolved oxygen, sediment loading and nutrient loading. These are all affected by the quantity of cool, clean water entering from the springs.

Environmental Concerns - Pacific Steelhead and Salmon. The Snake River is an important tributary to the Columbia River and an important fish migration pathway. Reclamation participates in providing flow augmentation water to aid Pacific species by purchasing water from Idaho surface-water rental pools, in an arrangement authorized by Idaho legislation (State of Idaho, 2006). The connection between aquifer/surface interaction and Pacific species is two-fold; not only do springs from the aquifer provide a large fraction of the summertime flows in the Snake River, but storage in the aquifer is a potential source of water to meet water needs in dry periods, including ecological needs.

Allocation, Markets and Prior Appropriation

Some economists assert that the prior appropriation system "does not facilitate the emergence of water markets" and that, therefore, "water is often not allocated to the highest value uses" (Hamilton et al, 2000). Others suggest that since water rights can be bought and sold, water *is* allocated by the market; in this view prior appropriation is not an alternate method of allocation but an alternate *property-right description mechanism* within a market allocation system (Slaughter, 2006). In the context of ground-water banking it is probably not important which viewpoint is correct; what is important is to understand that water isn't bought and sold in the ways we are used buying and selling other commodities. In Idaho, what is generally exchanged and marketed is not water itself but *the right to the use of water*, if and when it is physically and administratively available.

Markets. A simple definition of a market is "a place where many sellers display and sell their goods... a region or outlet for successful trading" (Lexicon, 1992). More formally, a functioning market includes (though perhaps imperfectly) the following characteristics (Medema, 1993):

- property rights
    - fully specified
    - exclusive
    - enforceable
    - transferable
- costs and benefits *internal* to the players
- adherence to moral norms
- adequate numbers of buyers and sellers
- no barriers to exchange
- adequate information
- homogeneous commodity

Preliminary work in the Ground-water Banking Project suggests that instances of conflict, waste, ecological harm or impeded economic development associated with water use can be traced back to a deficiency in one or more of these market or property-right requirements. Many of these deficiencies may be discussed in terms of *externalities* and *public goods.*

Externalities. An "externality" or "third-party effect" occurs when a cost (or benefit) of a transaction is borne (or enjoyed) by a group or individual not a party to the transaction. The core of the definition is that the cost or benefit is *external* to the decision process of the party undertaking the activity from which the cost or benefit flows. To economists, externalities are a problem in terms of equity (by the simple definition that it is unfair to either bear the costs or enjoy the benefits of others' economic activity) and efficiency (since the full cost or benefit is not considered in the decision, the decision cannot be optimum for society as a whole).

Not all unpleasant consequences of water allocation are externalities, though there is a tendency to call them such (Taylor, 2005). The reality of allocation of scarce resources to infinite wants, failure of enforcement, failure of adherence to social norms and market barriers can all be mistaken for externalities. The key element of an externality is that part of the cost or benefit of an activity is *external* to the decision process of the party engaging in the activity.

Public Goods. Public goods are goods that 1) can be enjoyed by one person without diminishing the enjoyment by another, and 2) that lack the property-right characteristic of exclusion. Typically in a market these goods do not attract resources commensurate with their value to society, because it is not rational for any individual to expend resources towards those goods, when others will continue to extract enjoyment and cannot be excluded (Medema, 1993).

EXTERNALITIES AND GROUND-WATER/SURFACE-WATER INTERACTIONS

Addressing externalities requires an understanding of their origins. In the context of ground-water/surface-water interactions, a necessary but not sufficient condition for an externality to exist is a hydrologic connection. A second necessary condition is for the hydrologic connection to *not* be recognized in the allocation system. Thus, Slaughter and Weiner (2006) identify the separate management of ground water and surface water (in jurisdictions that ignore the hydrologic reality of interconnection) as an "important failure to specify property rights." In Idaho prior to the Musser Case, any material harm that junior ground-water pumping caused to holders of senior spring rights was an externality. Today in Idaho, with the existence of conjunctive management rules, any such harm would be a failure of adherence to social norms, or a failure of the enforcement mechanism. Impacts of *senior* pumping are the result of our society's allocation decision and *not* externalities. They are not externalities because part of the opportunity cost considered by the senior pumpers is the market price the rights would command if sold. This implicitly includes the demand of holders of junior rights; their demand is therefore *internal* to the decision process.

Idaho's conjunctive management rules attempt to address one hydrologic externality, the potential negative impact of ground-water pumping on springs and river gains. Other hydrologic externalities still are unaddressed in Idaho. These include:

1. The positive impact to the aquifer of incidental recharge from surface-water irrigation. In total annual volume this far exceeds the externality that current conjunctive management rules address. Further, changes in surface-water practices have reduced this incidental recharge, with an

impact to springs of the same order of magnitude as the ground-water pumping that is addressed by the rules (Cosgrove et al, 2005).

2. The ecological cost to the river ecosystem of surface-water irrigation diversions. It may be argued that this is simply a result of our social decision to prefer irrigation to instream flows (an allocation decision). However, because current Idaho legal barriers largely prevent purchasing senior water for instream flow, the potential demand of environmental interests is not part of the opportunity cost considered by irrigators and the ecological cost is external to irrigators' decisions.
3. The excess benefit to one or more river reaches that is often generated as part of a transfer mitigation plan. This is small in volume relative to other externalities, but important in the context of economic growth since transfer of existing rights is virtually the only source of water now available for economic growth in southern Idaho.
4. Managed[3] recharge.
5. Retirement of existing ground-water pumping.
6. Providing surface water during times of plenty as an in-lieu supply to lands that otherwise would be irrigated with ground water.

These all are externalities because hydrologic connections exist but the property allocation system does not allow the costs or benefits to be internal to the decisions of those initiating the activities. The last three activities would cause the quantity of water stored in the aquifer to be greater than it otherwise would have been. They are currently externalities because there is no mechanism to assign ownership of the benefits. As expected for a case of positive externality, these activities currently take place at very low levels, if at all. Because of lack of specification of a property right, the market fails to properly signal the value they could have to all water users.

EXTERNALITIES AND GROUND-WATER BANKING

Ground-water banking can address externalities by quantifying and assigning ownership to hydrologic impacts. Reclamation and IWRRI have incorporated response functions (Cosgrove and Johnson, 2004) and basic financial accounting principles (double-entry accounting) in a "proof of concept" computer program that illustrates how a ground-water banking system could perform these functions. Incorporation of hydrologic tools allows adjustment for the hydrologic reality of migration and dissipation of impacts over space and time. Incorporation of a standard financial accounting method tracks ownership and prevents withdrawals

[3] The Idaho definition of managed recharge is physically placing water in the aquifer with the primary intent to increase storage, no matter the nature of the structure or location of recharge. This differs from the Arizona definition that managed recharge is intentional recharge that takes place in a natural (vs. human-made) channel or structure (Swieczkowski, 2003).

from ever exceeding the residual balance of past deposits. Effects are *internalized* by the assignment of a property right (ownership of banking chits or credits).

For new activities such as managed recharge or retirement of senior ground-water pumping, the assignment of ownership is straightforward. The proposed activity has not yet occurred, and the water it will cause to be stored in the aquifer will not have been there, but for the proposed activity. No obstacles exist to assigning ownership of chits to the person or entity who will cause that water to be stored.

On the other hand, incidental recharge has existed as an externality for decades. Any attempt to address the externality by assigning ownership to the incidental recharge will have an impact on property rights that were perfected in the presence of the externality. Great care is warranted. At least three potential owners could be identified:

1. The public as custodian of the environment. Those who believe that the environment was the first user of the water (and that irrigators were second in time) consider suggestions that environmentalists should buy water as "bizarre" (Green, 2003). An argument can be made that society as a whole bears the cost of reduction in ecological services due to removing this water from the river, and that therefore the public as custodian of the environment should own the incidental-recharge chits.
2. Senior surface-water irrigators whose diversions supply the incidental recharge. These users can logically assert ownership of the chits because their predecessors expended the resources to create the distribution systems, and they themselves own the water rights under which the diversion is authorized.
3. Ground-water users and downstream surface-water users (spring users and river users who rely upon river gains). These users may also assert ownership because they have expended resources to perfect water rights in the resulting aquifer storage, river gains and spring discharges. They undertook this activity in good faith, in accordance with the water-law environment that prevailed at the time. Further, communities have sprung up dependent upon the farm economy sustained by these water uses. Current Idaho law allows perfection of a water right in a waste stream but forbids the user to compel the waste to continue. However, Idaho's constitution (State of Idaho, 2003) authorizes the legislature to modify

> prior appropriation. An equity[4] and public-interest argument could be made that the property-right specification of rights in waste water should be changed; assigning chits to spring users would essentially be this kind of change.

In order that the assignment of chits may perform its economic function of sending signals to guide water-use decisions, water users who are not assigned chits must be required to purchase them in some manner. While the Coase Theorem of economics suggests that the distribution of water to canal leakage, aquifer use and instream-flows would equilibrate to the same point regardless of who owned the chits (Taylor, 2005), there are very real issues of equity (in the broader definition) and transfer of wealth to consider. Note, however, that *any* correction of an imperfect property specification potentially involves a transfer of wealth, because current patterns of ownership and prices of assets have equilibrated to the current condition with its externalities. For example, the conjunctive management rules, as they become fully implemented, are reducing the value of junior ground-water rights and are precipitating a transfer of wealth from those who are currently invested in junior ground water. On the other hand, leaving the externality unaddressed would have perpetuated what has been essentially a transfer of wealth from spring users and users of reach gains.

In summary, ground-water banking can potentially address current externalities as well as externalities of potential future beneficial activities. Using ground-water banking to internalize benefits of beneficial future activities, thereby promoting flexibility and economic opportunity, is relatively straightforward and could be implemented in the first step of an incrementally-developed ground-water banking plan. Using ground-water banking to address existing externalities will require considerable care and deliberation and might best be approached in a later step.

BARRIERS AND GROUND-WATER BANKING

Ground-water banking may help overcome the frustration environmental interests feel in the current inability to move senior water rights to instream-flow purposes. One mechanism (potentially available under current statute and policy) would be for Reclamation to acquire ground-water chits through providing in-lieu supplies in wet years, retiring ground-water rights, managed recharge or purchase. In dry years, Reclamation could negotiate with holders of water in surface-water rental

[4] In this context, equity is defined more broadly as "that part of the legal system built around the principles of natural justice and fair conduct, [and] specifically designed to deal with those cases where formal law would result in an unfair outcome" (Green, 2003). The economic problem of externalities is both an equity problem and an efficiency problem, thus both equity and efficiency arguments are appropriate in considering how to address externalities.

pools to use Reclamation's ground-water chits by irrigating with ground water instead of rental-pool water. In exchange, the surface-rental-pool water would be made available for flow augmentation.

Providing market access to water for all purposes, including ecological purposes, would provide procedural equity. It would also certainly reduce conflict; if a market mechanism existed for environmental groups to purchase water for instream flow, there would be little justification to pursue water via litigation.

PUBLIC GOODS AND GROUND-WATER BANKING

Many ecological and recreational uses of water include characteristics of public-goods; one person can enjoy the resource without diminishing the enjoyment of another, and additional participants cannot be excluded or compelled to pay. The market fails to capture all of the potential demand and therefore the price signal is an incorrect representation of the desires of society as a whole. Therefore, even with the provisions described above, ground-water banking might still not result in the optimum level of instream flows for society as a whole; as a public good, instream flows may not attract resources commensurate with their true value to society. In the case of individuals, "economic value may diverge markedly from willingness to pay" (Green, 2003). In the case of potential purchasers who are public institutions (such as Reclamation), willingness to pay is tied closely to the resources available from taxation. However, "for the efficient level of public investment to be achieved, the tax taken... must be equal to the efficient level.... Tax levels are unlikely to be set either in this manner or with this effect" (Green, 2003).

CONCLUSION

Instances of conflict, waste, ecological harm or stifled economic growth suggest flaws in an allocation system. Economic principles and the requirements of markets and property right systems may be used to examine problems with water allocation.

The economic concept of externalities can be used to explain allocation issues associated with surface-water irrigation, pumping of ground water, and enjoyment of spring discharges and river gains associated with the aquifer. Ground-water banking can be a tool to internalize some of these effects. If the effects are internalized, the signals sent to water users will promote decisions that more closely align the utilization of resources with the needs of society as a whole. Because current patterns of ownership have equilibrated to existing externalities and conditions, there is a need to proceed with great care and deliberation in ground-water banking policies that assign ownership to existing effects (such as incidental recharge from surface-water irrigation). Assigning ownership to the effects of future activities (such as retirement of ground-water pumping, providing in-lieu supplies, or managed recharge) is more straightforward because no one yet has developed a claim to ownership of the benefits.

Ground-water banking can also be a tool to facilitate the movement of water to ecological purposes. It certainly would promote equity of process, reduce the potential for conflict and move some water to ecological uses. However, the public-goods characteristics of water for recreation and ecological purposes may still prevent ground-water banking from facilitating the optimum allocation between recreational, ecological and other water uses.

REFERENCES

Cosgrove, Donna M., B.A. Contor, N. Rinehart and G. Johnson. 2005. Snake River Plain Aquifer Model Scenario Update: Hydrologic Effects of Continued 1980-2002 Water Supply and Use Conditions using Snake River Plain Aquifer Model Version 1.1. http://www.if.uidaho.edu/%7ejohnson/BaseCase_Final_v1-1_mod.pdf, accessed 24 April 2006.

Cosgrove, Donna M. and G.S. Johnson. 2004. *Transient Response Functions for Conjunctive Water Management in the Snake River Plain, Idaho.* Journal of the American Water Resources Association. Vol. 40 no.6, pp.1469-1482. December 2004.

Green, Colin. 2003. Handbook of Water Economics Principles and Practice. Wiley, West Sussex, England.

Hamilton, Joel R., D. Huppert, K. Boire, K. Casavant, L. Peters, J. Richards, A. Scott, P. Sorensen. 2000. Economics of Water Acquisition Projects. Independent Economic Analysis Board, at the request of the Northwest Power Planning Council. http://www.webpages.uidaho.edu/~joelh/IEAB/WaterAcquisition/, accessed 17 November 2005.

Idaho Department of Administration. 1994. Idaho Administrative Code, Idaho Department of Water Resources, IDAPA 37.03.11 - Conjunctive Management of Surface and Ground Water Resources. http://adm.idaho.gov/adminrules/rules/idapa37/0311.pdf, accessed 24 April 2006.

Idaho Department of Water Resources. 2006. Website: Surface-water Coalition Priority Call. http://www.idwr.idaho.gov/Calls/Surface%20Coalition%20Call/default.htm, accessed 24 April 2006.

Johnson, Gary S., R.L. Harris, B. Contor, D.M. Cosgrove. 2004. *Ground Water Right Transfers in the Snake River Plain, Idaho,* in The Water Report, Issue #10, December 15, 2004.

Lexicon. 1992. New Webster's Dictionary and Thesaurus of the English Language. Lexicon Publications, Inc. USA.

Medema, Lee. 1993. Professor of Forest Economics, University of Idaho, Moscow ID. Personal communication.

Raines, Richard T. 2004. Following the Law in Idaho: Legal and Institutional Impediments to Conjunctive Water Management. http://www.ucowr.siu.edu/updates/pdf/V106_A5.pdf, file posted 2004 and accessed 24 April 2006.

Slaughter, Richard. 2006. Richard Slaughter Associates, Boise ID. Personal communication.

Slaughter, Richard and J.D. Weiner. 2006. *Water, Adaptation and Property Rights on the Snake and Klamath Rivers.* Draft of article accepted for publication in The Journal of the American Water Resources Association.

State of Idaho. 2006. Idaho Code 42-1763B. http://www3.state.id.us/cgi_bin/newdist?sctid=420170063B.K, accessed 24 April 2006.

State of Idaho. 2003. Constitution of the State of Idaho, Article XV Section 5. http://www3.state.id.us/cgi-bin/constretr?sctid=003151505.K, accessed 29 September 2003.

Swieczkowski, Drew. 2003. Arizona Department of Water Resources. Personal communication.

Taylor, Garth. 2005. Associate Professor of Agricultural Economics. University of Idaho, Moscow ID. Personal communication.

EFFECTIVE WATER MANAGEMENT THROUGH FARMER PARTICIPATION

Yameen Memon[1]
Mushtaq Mirani[2],
Mustafa Ujjan[3]
Fiza Qureshi[4]
Erum Maria Rajpar[5]

ABSTRACT

The Indus Basin Irrigation System (IBIS), commanding an area of 15.08 million hectares (ha), is Pakistan's century old and largest contiguous irrigation system in the world. The main problem facing the system is lack of equitable and reliable delivery of water in the tails of the channels to almost 1.4 million small farmers (landowners of less than 2 hectares). Its mismanagement occurs due to pressure of influential big land owners and head reach farmers and rent seeking by the irrigation officials. Consequently, small farmers and tail enders of the irrigation system are unable to cultivate their lands and suffer from extreme poverty. To address this issue, institutional reforms have been introduced aiming to improve the water management. Through these reforms, irrigation management has been transferred to farmers groups called Farmer's Organizations (FOs) initially introduced by the Nara canal area water board (AWB) in Sindh .

The paper describes the involvement of empowered and organized members of 3,217 watercourse associations (WCAs) and 166 farmer organizations (FOs) at Nara canal system for the social and economic justice to the suffering farming community. About 55% is water equitably distributed trough FO managed chancels and 15% of irrigation water is saved to irrigate land to combat the poverty. In all 762 issues relevant to water distribution have been resolved through the conflict resolution committees in their respective distributaries. Interestingly, 30% new chairmen of FOs has been inducted in the organizations through democratic process of election after the completion of first tenure of the

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[1] Chief Executive, Management & Development Center and former Principal Social Scientist, International Water Management Institute (IWMI) , Hyderabad, Sindh, Pakistan. e-mail: yameenmemon@yahoo.com
[2] Professor Mehran University of Engineering & Technology, Jamshoro, Sindh, Pakistan
[3] Team Leader, Participatory Irrigation Management Transfer Project, Hyderabad, Sindh, Pakistan
[4] Gender & Development Specialist, Sindh Rural Support Program, Hyderabad, Sindh, Pakistan
[5] Program Coordinator, Education & Gender, Sindh Agricultural & Forestry Workers Coordinating Organization (SAFWCO), Hyderabad, Sindh, Pakistan

elected board of management of Farmers Organizations. This has been possible as 16,557 pertinent members of these organizations have been imparted relevant trainings. In addition the crop assessment and water charges recovery has been increased sufficiently to operate and maintain the farmer managed irrigation system to support institutional reforms process. In order to create effective linkages and coordination among organizations and with other line agencies and national and international organizations, farmer organizations council (FOC) has been established by these organizations. This paper also suggests policymakers to support institutional reforms on other canals to replicate the model of Nara Canal area water board.

INTRODUCTION

Water for agricultural use accounts for 96 percent of the Pakistan's available water of 170 billion cubic meters (BCM). Its use is increasing day by day and around 160 million people of the country are dependent on irrigation for food and livelihood. Around 70% of population irrigates their lands through the Indus Basin Irrigation System commanding an area of 15.08 million ha. It is the century old and largest contiguous irrigation system in the world. The main problem facing by the country's irrigation system is delivery of water to the small farmers (land owner of less than 2 hectares) and tail enders of irrigation channels in particular. The mismanagement occurs due to pressure of influential big land owners and head reach farmers and rent seeking by the irrigation officials whose salary is not commensurate with their living standard. Resultantly, small farmers and tail enders of the irrigation system are unable to cultivate their lands and they are suffering from extreme poverty. Water management crisis has led to wide spread conflict between different stakeholders (Dupont 2000) in the country. Therefore, effective water management system has been suggested through participatory irrigation management in the country to overcome the major problem of equitable water distribution.

In fact the system has been with multiple problems, including inefficient, unequal and unreliable delivery of water. This is considered to be due to the lack of users' participation in the decision of water management at all levels (watercourse, distributary, canal and river).

The participatory irrigation management (PIM) is described as transferring of irrigation canal management to farmers groups called Farmer's Organizations (FOs) from state control to common property resource (Bandaragoda 1999).

The paper describes the involvement of members of farmer organizations for the social and economic justice to the farming community in general and small and tail end farmers in particular to deliver their due share of water to irrigate land to combat the poverty. In addition these organizations have made commitment to strength their organizations at other part of the system through joint efforts and support institutional reforms process. The paper also presents some of the suggestions for the planners and policy makers to replicate the model to other areas.

Management of Water Resources through Participatory Irrigation Management

In Pakistan the issue of management of water resources through participatory irrigation management was addressed by the World Bank sponsored National Drainage Project (NDP) Program during 1998. The institutional reforms program in irrigation and drainage system was envisaged to form watercourse associations (WCAs) and federate them as farmer organizations (FOs) at distributary canal level. In addition at main canal level, canal area water boards (AWBs) and for river basin Provincial Irrigation and Drainage Authority (PIDAs) were established in their respective four provinces (Punjab, Sindh, Northern West Frontier Province, and Balochistan) of Pakistan. Accordingly in 1997, the Sindh Assembly passed Irrigation & Drainage Authority (SIDA) Act. And after two years first canal area water board was established at Nara Canal command area. Nara Canal oftakes from the Sukkur Barrage (3 barrages in Sindh province at Indus River). This is the largest off taking canal of Sukkur Barrage system in terms of design discharge (13,600 cusecs) and second largest in terms of culturable command area (1.02 million hectares)

Irrigation management transfer (IMT) is the full or partial transfer of responsibility and authority for the governance, management and financing of irrigation systems from the government to water user associations (Vermillion 2003). PIM usually refers to the level, mode, or intensity of user participation that would increase farmer responsibility and authority in the management process (Svendsen et. al. 2002).

Nara Canal is the first in Sindh, Pakistan to come under IMT. The Nara Canal is a sort of natural river and was termed as Hakro River in olden times. It is 375 km long, traversing a zigzag course from the northern part of Sindh and culminates desert portion of South Eastern Sindh. The entire Nara Canal system comprises of three (03) main canals, ten branch canals, 166 distributaries, 4,317 watercourses (3,217 watercourse offtake from distributaries and 1,102 offtake direct from main and branch canals). It is divided into two (02) parts the upper part which runs from Sukkur barrage to Jamrao Head, 190 km long. The second part runs from Jamrao Head to its end Nara Tail, 183 km long. The Nara Canal system was accompanied with natural drainage infrastructure and fresh water bodies supplied water through escape canals off taking from Nara.

It is widely assumed that irrigation management transfer (IMT) to the farmers through institutional reforms will manage the water equitably to the tail enders and small farmers to improve the efficiency, productivity, and sustainability of irrigation to combat the poverty (Vermilion, 1991). Several countries have experienced the positive results of the IMT, such as the USA, Turkey, Mexico, Australia, Sri Lanka and Nepal. A farmer-controlled community irrigation system was found to have led to a better design of the irrigation system and to have increased the problem-solving capabilities of local farmers (Alfonso, 1981).

Establishment of Farmer Organizations (FOs)

To implement the reforms, initially International Water Management Institute (IWMI) was contracted under the National Drainage Program (NDP) for pilot action research in Sindh province. It aimed to test the viability of farmer managed irrigation system. The IWMI successfully formed 330 watercourse associations (WCAs) at the watercourse level, and federated them as farmer organizations (FOs) at fourteen (14) distributary/ minor canal level using the extensive well tested social mobilization process (Memon et. al. 2000). After some time efforts were made by other organizations like On-Farm Water Management (OFWM) of Sindh Agriculture Department, Sindh Agriculture and Forestry Workers Coordinating Organization (SAFWCO) – an NGO and Sindh Irrigation and Drainage Authority (SIDA) to form FOs on additional distributaries and minors in Nara Canal Area Water Board command area. Consequently, by the end of year 2002, watercourse associations on 3,217 watercourses and 162 farmer organizations were formed and registered under SIDA Act 1997. In all 141 FOs have been able to sign irrigation and drainage management transfer (IDMT) agreement during 2001-03 and took over responsibility of distributing water equitably from head to tail of distributaries and watercourses and operating and maintenance of distributaries.

Empowerment of FOs

Empowerment denotes an increase in the power an actor or group of actors commands. Power is defined here in relational terms, as a capacity that actors have or lack in the transactions between themselves. Anthony Giddens (1979) has defined power as transformative capacity, the ability to bring about changes in the state of things and relations among actors. Through the exercise of power, actors seek to get others to comply with their wants. Giddens argues further that power engenders relations of autonomy and dependence.

FOs were empowered through proper legislation and transfer of functions of distributaries, to help them play their due role in water management.

Capacity is the ability of the person or organization to do things with maximum competence. The organization needs to be effective in the delivery of the services and efficient use of resources (Alaerts et. al.1991). Enhancing the abilities of the leaders to smoothly establish the institution and perform the designed functions is essential. Human resource development and capacity building program ensures sustainability of the institution, laws and regulation can efficiently be used, and more resources can be mobilized.

Capacity building must not be merely viewed as a training program aimed at bridging gaps in knowledge and skills among farmers and agencies but also as facilitating the change process. A blend of skills and attitudes needs to be imparted at all levels which also includes policy makers (Peter 2003).

The training needs of the members of farmer organizations through intensive interaction by convening individual and organizational meetings, and participatory rapid appraisal were assessed. The capacity building program was identified and initiated after the formation of FOs on distributaries and watercourses. It was designed to form and strengthen the farmers' institutions as well as develop the necessary skills particularly water management among the leaders of these institutions.

Particularly training on the following fields was imparted for enhancing the capacity and awareness of the members of organizations:

- Discharge measurement and water management at watercourse and distributary canal level;
- Organizational set up and rules and regulations;
- Crop assessment, and collection of water charges; and
- Operation and maintenance of distributaries and minors;
- Financial Management , business plan and book keeping
- Conflict resolution

The training program in the above fields was organized for the 16,557 pertinent members of watercourse and distributary canal organizations. Teaching methods include: theoretical concepts, hands-on-practice and interaction discussions and field exercises.

FOS ACHIEVEMENTS

The make the institutional reforms a success, the following efforts are being made by the watercourse associations and farmer organizations:

- Water users irrespective of land holding, tenancy status and social and financial status, have been able to sit together and discuss common issues breaking the skepticism that big landlords and privileged water users can not sit together with smaller deprived land owners. This new friendship among farmers has created the cohesion among various segments of society and communities.

- Responsible members of FOs are maintaining record of water availability in the channel by measuring the flow of water in watercourses as well as in the distributaries through calibrated gauges and using float method. And distribute water according to the due share of the water users.

- Collective efforts utilizing human and capital resources are being made by these organizations for de-silting their distributaries and watercourses particularly during the canal closure period. During the lst four years 162 FOs have successfully desilted 13.76 million cubic meters of silt at self help basis/ donations from 40% share of water charges collected by FOs. This action is a substantial saving for the government who would otherwise had to pay from their treasury.

- Proper assessment of crop command area and recovery of water charges from respective landowners is being done by the responsible members of organizations on regular basis and so far from (2001 to 2004), 141 FOs have deposited Pak Rupees 70 million (1.16 Millions US $) in the account of Nara Canal Area Water Board as 60% share of water charges where about 20 million Pak rupees are retained by these organizations for maintenance of the channels and operational expenditures.

- Almost all organizations have constituted conflict resolution committees; having by and large elder and reputable members on these committees with the main purpose to resolve the conflicts mostly on water issues.

- The elected members of farmers organizations are regularly involved in the decision making processes at canal area water boards and irrigation & drainage authority boards by participating regularly. Election process to support democracy in the organizations is transparently accomplished. Out of 162 FOs successfully completed their first tenure have entered into re-election process and so far 141 have completed the process of re-elections. These re-elections resulted 30% new faces as leaders of FOs.

- FOs have joined hands together by establishing the farmer organizations Council (FOC) involving almost all farmer organizations mainly for coordinating and linkages within and outside organizations.

- To strengthen organizational role of FOs, under the World Bank funded irrigation rehabilitation project, FOs have been assigned the role of employer and all construction contracts were designed, supervised and implemented under the instructions of FOs. Presently 10 FOs are managing the rehabilitation works of irrigation channels amount to Rs.73.5 million. Out of these, one contract is a community managed contract, the first of its kind, where the FO has awarded the contract, is making payments and finalizing the work done. This had greatly boosted the confidence and capacity of the FO in technical matters as well.

Impact of Institutional Reforms on Water Management

The efforts made by the organizations have brought following impacts on the small farmers and tail enders are:

- Frequently discussions by the members of organizations for equitable water distribution, almost 70 percent (1.4 m small farmers and 44 (26%) tail end distributaries) water is equitably distributed; consequently 20% of cultivation intensity as compared to the pervious years (1999 to onwards) has increased. Additional 0.37 million hectares of land has brought under cultivation.

- With the efforts of organizations, the overall equity of water situation at the tails of channels has been improved by 55%, measured by FOs and AWB staff.

- Since last 3 years, almost all watercourses and distributaries are being de-silted by utilizing human and capital resources of organizations to save around 15% of irrigation water to cultivate more land by the members.

- The responsible members of the organizations are instrumental in properly assessment of crop command area (20 % more as compared to base year of 1999) and recovery of water charges increased by 17 %. Legally 60 % of water charges collected are being paid to Nara Canal area water board for service delivery, whereas the rest collected charges (40%) are being retained by the organization for operation and maintenance of their distributaries and organizational expenses.

- In all 762 issues relevant to water distribution have been resolved through the constituted conflict resolution committees in their respective distributaries.

- One case can be quoted that: FO works in the command area of Sanhro distributary off taking from jamrao Canal in Mirpurkhas irrigation sub division. After the re-election of FO in March 2005 the Board of Management (BoM) was replaced with a new body. This BoM consist of members of group belonging to the opponent group of the previous body. With the taking over of the system by the newly elected body incidents of outlets tempering increased causing shortage in the tail of the channel. The tail end growers started protesting against the shortage of water in the tail of the channel in front of AWB engineers. The newly elected body of FO headed by its Chairman - Mr. Saleem Khan Malkani arranged general body meetings of the FO to sort out more reasons for the shortage of water in the tail of the channel, monitoring committees for formed, fine was imposed on the owners of the tempered outlets and water availability in the tail portion was restored through indigenous efforts of the FO and conflict resolution mechanism embedded in the social set up.

- Within last four years, two times elections have been held at the watercourse and distributary level. At several places new leadership have been inducted. Around 70 % same leadership has been elected considering their motivated efforts for the organization.

- By August 2005, Sindh province local bodies elections were held, a sizeable number of FO office bearers (total 137) were elected for different tiers of Local Government system. This reflects the confidence of the population in the FO leaders for representing them at more enhanced level and emergence of a new class of local leaders through the institutions of FOs.

- In order to create effective linkages and coordination among organizations and with other line agencies and national and international organizations, Farmer Organizations Council (FOs) have been established. The organization has done:

  - Providing a platform for member FOs to have a united voice on the matters of interest of farming community and agriculture .
  - Established linkages with national and international organizations like Global Water Partnership, International Network for Participatory Irrigation (INPIM), etc. to strengthening the concept of PIM
  - Arranged capacity building and awareness raising programs for the member FOs and coordinating them with AWBs and SIDA activities.
  - Members of FOC have got opportunity to participate in national and international forums such as: global water partnership, country and regional water partnership.

Suggestions for Sustainability and Replicating

In order to replicate the Nara Canal Area Water Board model, following suggestions are made:

- Policymakers to support institutional reforms on other canal area water boards may create influences and pressures to replicate the model of Nara Canal area water board on other canals of IBIS system. FOs should be provided enabling environment, political support and their capacity building.

- Since the introduction of intuitional reforms, farmers have been mobilized to form FOs. Through its legal and technical component, FOs have been able to:

- Equitably distribute water as per share
- Realistically assess the crop cultivated and collect water charges
- Timely maintain the irrigation channels for better service delivery

- When compared with the channels, where FOs are not functional, it is observed that there is serious mismanagement of water resources and water delivery is badly affected and small farmers and tail enders are not getting their due share of water. Thus the promise of institutional reforms seems largely fulfilled through the FOs achievements.

- To get the full benefit of institutional reforms and increasing the income of farmers agricultural support services for the organizations would be required to give advice on crops, pesticides, corporate management methods, market intelligence and development of an agribusiness plan.

- Through intuitional reforms process of FOs formation should be expedited on the canals which are working under the traditional bureaucratic mode of management.

- There should be proper monitoring of the institutional development of FOs and area water boards and they should provided technical support for their organizational strengthening.

- Political will is must for successful replication of reforms.

REFERENCES

Alaerts G. J., T.L. Blair, H. Saveniji, M.W. Blokland and P. Van Hofwegen.1991. Procedures and Partners for Capacity Building in the Water Sector. In A strategy for Water Sector Capacity Building, *Proceedings of the UNDP Symposium, Delft*.

Alfonso, F.B. 1981. ‘Assisting Farmer Controlled Development of Irrigation Systems’ in David C. Korten and Felipe B. Alfonso (eds) *Bureaucracy and the Poor: Closing the Gap*. Singapore: McGraw-Hill.

Bandaragoda, D.J., 1999. *Institutional change and shared management of water resources in large canal system : results of an action research in Pakistan, 36*, International Water Management Institute, Colombo.

Bank, W., 2001. 'Electronic learning guidebook for Participatory Irrigation Management', (5/9/01)

Dupont, A., 2000. 'Food, water and security: what are the connections?', *Food, water and war: security in a world of conflict*, ACIAR, Canberra.

Gidens, A., 1979. Central Problems in Social Theory. Action, Structure and Contradiction in Social Analysis. Barkeley: University of California Press.

Memon, Y., M. Talpur and H. Murray-Rust, 2000. Capacity Building for Participatory Irrigation Management in Sindh Province of Pakistan. *Farmer Managed Irrigated Agriculture Project. IWMI Pakistan National Program Research Report.*

Raymond , Peter J. “*Capacity Building for PIM – The case of Andhra Pradesh*” paper presented at the FAO/ICID International Workshop on capacity Building for Irrigation and Drainage,
Montpellier, France 2003.

Sindh Irrigation & Drainage Authority. 2005. Monthly Progress Report. Social Mobilization Group, Sindh On Farm Water Management Project. April,

Svendsen M., and G. Nott. 1997. Irrigation Management Transfer in Turkey: Early Experience with a National Program Under Rapid Implementation. *Short Report Series on Locally Managed Irrigation. International Irrigation Management Institute. Colombo, Sri Lanka. Report No. 17*

Vermillion, D.L., 1997. *Impact of irrigation management transfer: a review of evidence, 11*, International Irrigation Management Institute, Colombo.
Vermillion, D.V., 2000. *Guide to monitoring and evaluation of irrigation management transfer*, The Japanese Institute for Irrigation and Drainage, Tokyo.

Vermillion, Douglas L., 1991. "The Turnover and Self Management of Irrigation Institutions in Developing Countries", a discussion paper, IIMI, Colombo.

IMPROVING CANAL WATER MANAGEMENT THROUGH PARTICIPATORY APPROACH: A CASE STUDY ON SECONDARY CANAL (POTHO MINOR), SINDH, PAKISTAN

Bakhshal Lashari[1]
Ali Asghar Mahesar[2]

ABSTRACT

Improvement in canal water management requires the strong and stable relationship and trustworthy among the water users in the command area of Watercourse (Tertiary canal) and Distributary/Minor (Secondary canal) and canal operating agencies. The potential conflicts on water distribution equity among the water users at secondary level canal could be achieved through establishing Farmer Organization (FO) at Distributary and Watercourse Associations at watercourse, training to the farmers, appropriate water measuring mechanisms and proper maintenance.

Potho Minor is the secondary canal level network of irrigation system in Pakistan. The Farmer Organization on the minor was established in 2000. However, the process of social mobilization was started in 1999. Present study was carried out to assess the status on water delivery to farmers, water use efficiency and farmer's role for improving water distribution for sustainable irrigated agriculture.

Based on data collected and analyzed in command area of the Minor, the status of irrigation water management demonstrates that the water delivery to the farmers along the minor length fluctuates between 25-190 percent, water availability is only 68 days out of 168 days allocated for the crop season, but it is abundant as estimated 5.9 mm/day against the required 2.83 mm/day. This all mismanagement has resulted in 34 percent system efficiency and 10 to 114 percent watercourse-wise efficiency.

However, the participation of water users from Watercourse Associations and Farmer Organization in the maintenance of the distributaries/minors for sustainable irrigation management has proved that the cost of maintenance can be significantly minimized and work can be done in time. The maintenance cost estimated was about US$ 0.25 (Pak Rs. 15) per acre of land and the substantial benefit accrued was observed that the head-tail water delivery performance ratio improved significantly, though the head DPR was substantially decreased.

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[1] Professor, Institute of Irrigation and Drainage Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan
[2] Deputy Director, Water Resources Engineering, Sindh Irrigation and Drainage Authority, Hyderabad, Sindh, Pakistan

Further, paper highlights the lessons learned from the maintenance activities and concerns for the future of Farmer Organizations.

INTRODUCTION

In Sindh, Pakistan the institutional reforms in irrigation sector started in 1997 and Sindh Irrigation and Drainage Authority (SIDA) was established. The over all objective of the institutional reforms is to operate and maintain Irrigation and Drainage System with reliable service delivery on condition agreed up on by the end users.

The differences in water deliveries to different sub systems, head-end areas receive significantly more water than their share, and tail-end areas receive comparatively less irrigation water, therefore, the actual water distribution pattern failed to meet the targets set down at the start of each season. (Kijne D. Murray-Rust and W. Snellen 2002, and N.Bhutta and Vander 1992).

The most important component of irrigation system is to organize farmers. Once organized in an effective manner, farmers will demand equitable water distribution. In fact, the organization cannot be sustained unless this objective is achieved. Also, they will have a keen interest in reducing discharge variability. The main advantage is that significant increases in agricultural productivity can be expected (Zaigham and M.Kuper 1998).

The poor function of the irrigation system in Pakistan has been since the year 1960's. This under performance is mainly due to the scarcity of surface water. The previously planned scarcity of surface water now manifests itself inadequacy, un-reliability and inequity in the distribution of surface water for farmers at watercourse. Now, these discrepancies lead to other problems like water logging and salinity (Stosser 1997).

There is a need for all countries in the region to upgrade their human resources in number and know-how and improve their institutions so as to provide an efficient working environment in which trained human resources can be most effective. Most of the countries, however, are sufficiently aware of the problems. The technical know-how exists or gaining access to it is relatively easy, but there are major difficulties and a lack of experience in managing the application of technology on a large scale in order to solve and avoid problems or to establish desirable programs or practices. In most countries, for example, the technical community is well aware of what constitutes good irrigation, of how to be water efficient, how to determine crop consumptive use and irrigation scheduling, and how to avoid salinization and erosion. What is not so well known is how to structure and implement efficient and cost-effective procedures to "set in" the available knowledge within water user communities to ensure continuous application of proven practices, thereby accomplishing sustainable agriculture (J. F. Alfaro 1995).

The performance evaluation of an irrigation system at primary and secondary sub-system levels is in isolation from the performance evaluation of an irrigation system at watercourse and farm level that would not provide full understanding of the system. However, little work has been done on the performance of the surface water supply system at watercourse level (Perry 1996).

An orderly system of distributing water must be in place through some existing and respected regulatory framework for allocating water among farmers—rules and procedures defining rights and responsibilities; priorities in case of shortage or excess supplies; penalties for breach of rules, and so on. If this is not the case—or if regulations are not observed (if farmers take water at will, manipulate gate settings, tolerate significant interference in water, or do not pay assessed charges) then there is no immediate scope for improving water distribution through pricing (C.J. Perry 2001).

STUDY AREA

Potho Minor Farmers Organization was formed in 2000 and an agreement was signed with Canal Area Water Board (CAWB). Process of social mobilization for forming the organization was started by the International Water Management Institute (IWMI) in 1999. The responsibilities of FO includes: Operation and maintenance of minor and drainage infrastructure, assessment and collection of abiana (Water charges), water management for fair distribution of water to the

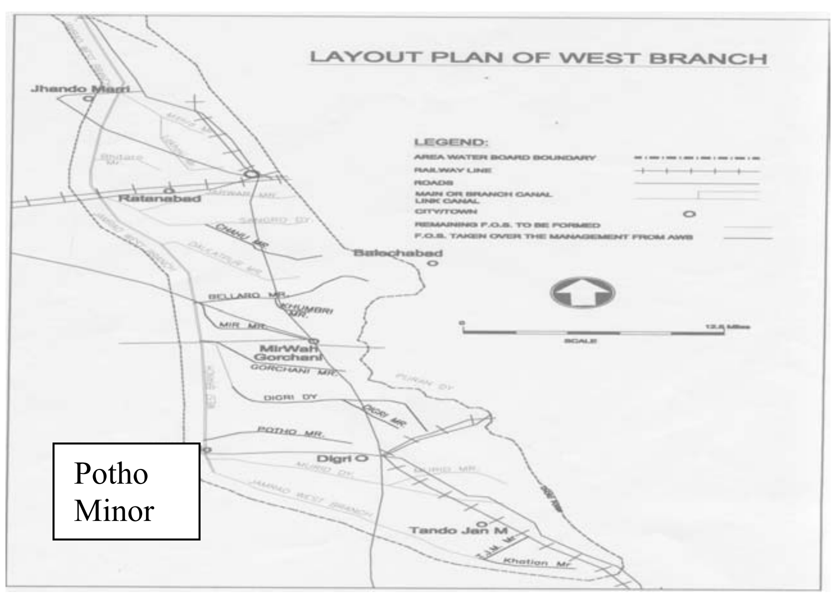

Figure 1. Location Map of Potho Minor Off taking from West Branch of Jamroa Main Canal.

farmers/ water users as per their entitlement, receive water supply as per the design discharge at head regulator of the minor and conflict resolution if arises at any time. The location map and salient features of the Minor are shown in Figure 1 and Table 1. Note: Data was recorded from September 2002 to March 2003.

Table 1. The Salient Features of the Potho Minor.

Description	**Detail**
Name of minor	Potho minor
RD taking off from West Branch	215.0
Design Discharge (cusecs)	29.9
Length of minor (RD)	33.11
Number of water courses	19
Number of lined water courses	3
Gross Commanded Area(acres)	9063
Cultural Commanded Area (acres)	8 396

RD= Reduced distance

DATA COLLECTION

At Minor level, gauges were installed at head-middle and tail sections of the Minor. The Minor length was divided in three equal parts considering command area. These gauges were calibrated and rating was developed (Discharge vs. water depth). To get the accurate data, the gauges were periodically checked and calibrated accordingly.

At watercourses level, the rectangular sections having length 20 feet, depth 2 feet and width 2 feet were constructed in each watercourse. The purpose of having the rectangular section was to have the stable section where the gauges can be installed or used. The sections were calibrated and ratings were developed for all watercourses. The outlet structures were not used as measuring device because most of them were tampered with or frequently being tampered.

Farmer Organization (FO) and Watercourse Associations (WCAs) were actively involved in gauges installation, construction of rectangular sections and daily monitoring gauge levels and recording on record book. To make reliable data the FO members were provided training on water measurement, canal operation, development of a business plan, collection of irrigation fees and development of effective and manageable maintenance plans

Crop data was surveyed physically and recorded for each watercourse separately. Using this data cropping pattern and cropping intensity were obtained. However, the design data was collected from the Irrigation and Power Department, Government of Sindh.

RESULTS AND DISCUSSIONS

Water delivery and distribution system

Total water delivery to the head was estimated 6177 acre feet (AF) for a period of 68 days out of 168 days running of the Minor for full crop season (winter season); if, the continuous full supply of water would have been given according to design then the minor would have received 9963 AF. This actual delivery of 6177 AF is 62% of design delivery, whereas, the Minor was closed in rotation for more than 60% of winter) season.

Figure 2, shows that the fluctuation in head gauge is varying from 25% to 190% in the Rabi season. More variation has been taken place in the months of November, January and March. The variation at middle gauge is between 45% and 26% in Rabi season. However the major variation at middle gauge has taken place in the months of December, January and March. The fluctuation at the tail gauge has remained between 50% and 28%. The worst effected months were November, December, January and March.

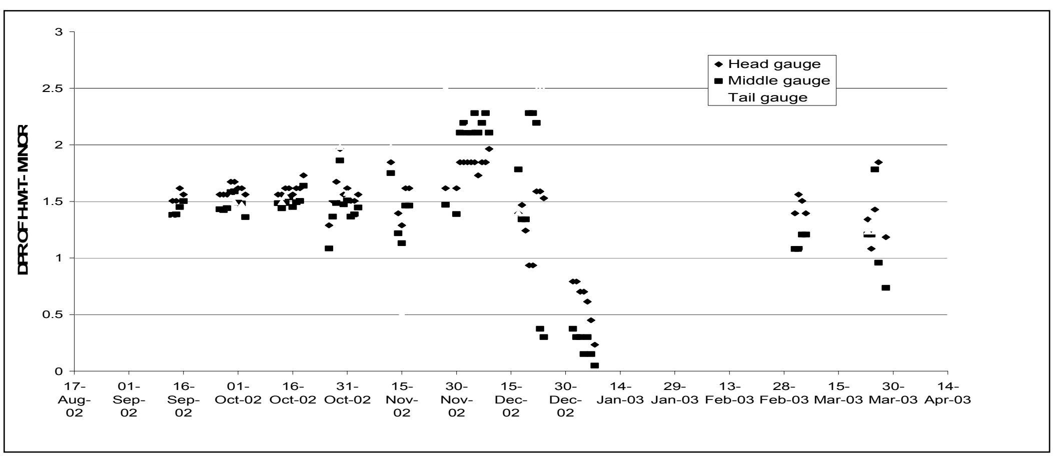

Figure 2: Water Delivery Performance Ratio at Head, Middle and Tail Gauges of the Minor

Table 2. Observed Discharge and Volume Indices for all Watercourses

Water-courses number	Design discharge cusecs	Actual discharge when flowing (68 days), cusecs	Average actual discharge over Rabi season (168 days), cusecs	Volume, acre-ft
151/2R	1.71	4.76	1.89	628.60
151/3R	1.50	2.53	1.01	333.74
151/4R	1.00	1.34	0.53	176.38
150/2L	1.14	1.96	0.78	259.16
153/1R	0.90	2.03	0.81	267.48
150/3L	0.77	1.81	0.72	238.84
154/1L	1.68	2.63	1.05	347.48
161/1AR	0.95	1.76	0.70	231.80
161/1R	1.13	1.96	0.78	259.08
160/1L	1.84	2.72	0.95	315.20
160/4AR	1.13	1.71	0.60	198.12
160/4BR	0.80	2.76	0.97	320.50
160/2L	1.80	2.96	1.03	343.56
169/1BR	0.96	2.74	0.96	317.38
160/3R	0.18	1.93	0.67	224.02
160/4L	0.81	2.11	0.74	244.66
164/2T	1.50	2.63	0.92	304.84
164/1AT	2.10	2.53	0.88	293.50
169/1AT	1.08	1.48	0.52	171.16

Table 2 expresses the overall view that how each watercourse command area is receiving actual water supply against the designed water supply and crop water need. The system (all command area and watercourses) receives water 68 days against the planned crop season of 168 days (60% system is closed). However, the actual supply in each watercourse is varying between 345% and 120% of designed discharge, again if, it is distributed among all watercourse for planned 168 days of crop season, the average discharge becomes between 110% and 53%.

<u>Water Application in Command Area of Watercourses.</u>

The assessment of water application in command area of the Minor is based on the actual measurements of water flows and cropped area for the Rabi (winter) season. The results are shown in Table 3.

Table 3: Delivered Volume, Required volume, Efficiency and Sufficiency of Watercourses

Watercourse number	Measured volume (acre-feet)	Water requirement (IPD 1993)* (acre-feet)	Efficiency %	Sufficiency %
151/2R	629	88	10	715
151/3R	334	124	26	269
151/4R	176	88	36	200
150/2L	259	118	32	220
153/1R	267	126	33	213
150/3L	239	51	15	468
154/1L	347	179	37	194
161/1R	232	152	47	152
161/AR	259	168	46	154
160/1L	315	184	42	171
160/4AR	198	213	76	93
160/4BR	321	109	24	293
160/2L	344	128	27	268
169/1BR	317	110	25	288
160/3R	224	31	10	713
160/4L	245	78	23	314
164/2T	305	219	51	139
164/1AT	294	186	45	158
169/1AT	171	275	114	62
Totals	5476	2628	Avg: 34	Avg: 208

(*The calculations are based on recommended values of crop water requirement published in irrigation manual by Irrigation and Power Department, Government of Sindh 1993.)

The results indicate that the water use efficiency of each watercourse command area is ranging between 10% to 114%. If the irrigation water is properly managed and applied then the efficiency could have been much higher as determined ranging between 715% to 93%. The data gives the impression that the water was not properly distributed and managed as per crop need and soil holding capacity.

Table 4. Received Volume, Culturable Command Area (CCA), Potential Cropped Area and Potential and Assessed Cropping Intensity for all Watercourses.

Water-course number	Received volume, acre-feet	CCA, acre	Delivered volume over cultivated area, feet/acre	Potential area, acre	Potential cropping intensity %	Assessed intensity %
151/2R	629	614	1.02	330	54	8
151/3R	334	548	0.61	221	40	15
151/4R	176	357	0.49	137	38	19
150/2L	259	392	0.66	165	42	19
153/1R	267	375	0.71	164	44	21
150/3L	239	274	0.87	157	57	12
154/1L	347	596	0.58	200	34	17
161/1R	232	339	0.68	174	51	34
161/AR	259	454	0.57	175	38	25
160/1L	315	649	0.49	211	33	19
160/4AR	198	393	0.50	134	34	37
160/4BR	321	279	1.15	240	86	29
160/2L	344	648	0.53	241	37	14
169/1BR	317	272	1.17	210	77	27
160/3R	224	69	3.25	187	272	38
160/4L	245	286	0.86	183	64	20
164/2T	305	520	0.59	176	34	24
164/1AT	294	745	0.39	174	23	15
169/1AT	171	253	0.68	68	27	43
Totals	5476	8063	Avg: 0.68	3449	Avg: 43	Avg: 21

Table 4 shows that water was delivered for each acre of culturable command area on average 0.68 foot. However, water delivery for watercourses varies between 3.25 acre-feet in 160/3R to 0.39 acre-feet in 164/1AT.

The potential cropped area in the Minor, using averages for the intensities of different crops, would have been 3449 acres or 43% of the CCA. However, the potential cropping intensities of the watercourses vary between 23% and 86%. Only for watercourse 160/4AR, the cropping intensity is 37% as was assessed while the delivered volume of water is only enough for 34%, here shows that the deficit irrigation was applied. However, almost for all watercourses the potentially cropped area is higher than the assessed, therefore, the delivered volume is enough for 27% designed cropping intensity. It is difficult to exactly interpret the data in Table 5. Nevertheless, the analysis provide insight in the water distribution, its use, the quality of assessment, possibly changes in CCA and many other things.

Role of Farmer Organizations

Farmer Organizations established in Sindh Province including Potho Minor Farmer Organization have been given responsibility of operation and maintenance of the secondary channel (Distributary/minor level canals). The performance assessment has been made for some of the FOs including Potho Minor.

Table 5. Maintenance Input into FO Channels.

Distributary	Man-days	Tractor hours	Imputed Cost (Rs)	Earthwork (m^3)	Cost (Rs/ha)
Heran	1157	58	124100	7411	24.85
Khadwari	301	16	49275	n/a	39.59
Rawtiani	586	35	64025	1351	17.50
Bareji	1020	14	105700	5601	18.23
Mirpur	1311	120	172650	9993	26.29
Potho	***979***	***17***	***113611***	***8138***	***34.80***
MAW	427	30	44625	3806	28.76
DhoroNaro	2055	292	249375	7376	46.03

The imputed cost of this activity is calculated on the typical labor and machinery hire rates prevailing at the time of the survey. Based on an average of Rs. 100 per day per person and between Rs.150-175 per tractor-hour, the grand total is just over Rs. 800,000. On an average basis the cost is almost Rs.25 per ha ($0.45) which represents about 40% of the typical irrigation water fee or abiana that farmers are expected to pay.

Table 6. Hydraulic Condition of Distributaries before and after Maintenance

Distributary	Before Desilting			After Desilting		
	Head	Tail	Ratio of Head:Tail	Head	Tail	Ratio of Head:Tail
Heran	1.36	0.38	3.53	1.31	0.51	2.55
Rawtiani	1.71	1.71	1.00	1.54	1.71	0.90
Tail	1.49	1.20	1.23	1.15	0.96	1.20
Mirpur	1.02	0.39	2.64	0.94	0.66	1.44
Bareji	2.13	1.63	1.30	2.13	2.36	0.90
Sanrho	1.29	1.11	1.16	1.34	1.58	0.85
Belharo	1.11	0.36	3.07	1.07	0.79	1.35
Digri	1.17	1.12	1.04	1.04	0.90	1.16
Potho	***1.42***	***1.15***	***1.23***	***1.20***	***1.12***	***1.07***
Khatian	1.31	0.65	2.00	1.25	1.35	0.92
Bagi	0.58	0.80	0.72	0.71	1.36	0.52

Looking at the ratio between head and tail delivery performance ratio (DPR) values before desilting, the degree of inequity can be clearly seen from Table 6. In only one canal (Bagi minor) was tail end DPR values higher than the head: in all other canals head end values were higher than tail end. At Heran and Belharo head end values were over three times as high as tail end values.

After desilting the picture changed considerably. Average discharges into canals were only 20% above design: overall in the area discharges are low after desilting because it is the coolest season of the year and wheat in some areas is beginning to mature. However, tail end DPR values were, on average, also at 120% of design indicating almost uniform distribution. Data demonstrate that the inequity between head and tail was substantially reduced. However, many tail end areas got more water than the head, but in reality this will slowly be reversed as canals silt up again during the year.

LESSONS LEARNED AND FUTURE CONCERNS FOR MAINTENANCE ACTIVITIES

The ability of Farmer Organizations to take substantial responsibility for maintenance at secondary canals in Pakistan is a relatively recent phenomenon and certainly one that ten years ago would have been viewed as more or less impossible. However, the process is still in initial stage and there remains a lot of work to be done to develop a sustainable approach for operation and maintenance.

It is also clear that in a comparatively short period of time, and certainly in no more than two or three days if people work hard, it is possible to completely desilt secondary canals and restore them to their original design condition. This level of input does not seem unreasonable and we can speculate that if other conditions remain in place then it will be possible to expect similar inputs into the future.

There were substantial hydraulic benefits. In virtually all locations the inequity of water distribution between head and tail was reduced, and in several cases previous inequities were reversed with tail end water users getting a slightly higher proportion of available water than head enders.

Based on these concerns it would be premature to suggest that one the basis of a single activity within the context of a fairly intensively managed that the Farmer Organizations can undertake all aspects of maintenance into the future. There is still a long way to go before they develop the technical skills and the managerial capacity to maintain canals, repair infrastructure, and upgrade it as and when the need arises.

On the other hand, the Irrigation Department has been unable to do this for many years despite technical training, manuals and guidelines, and financial resources. So the result may be one that is no worse than previous conditions but one that does hold out some hope for the future that the current water users have the responsibility for looking after their own affairs.

CONCLUSIONS

The system overall views that it has received water 68 days against the planned crop season of 168 days (60% system was closed). However, each watercourse was getting discharge between 345% and 120% of designed discharge. If, the available water would have been distributed among all watercourses for planned 168 days of crop season, the average discharge could have been between 110% and 53% and that rotation period could have been reduced significantly.

The water use efficiency of each watercourse command area was between 10% and 114%. If water was properly managed and applied, then the efficiency could have been reached between 715% and 93%. This poor efficiency is due to unreliable supply of water and continuous rotation system. This also shows that there is no check and balance system and coordination among stakeholders to manage the irrigated agriculture system in proper manner.

The cropping intensities in all watercourses command area were between 43% and 8%. If, water were properly managed then potentially cropping intensities of the watercourses would have been between 86% and 23%. Therefore, the delivered volume of water would have been enough for designed cropping intensity of 27% of winter season and the average potential cropping intensity for the Minor command area would have been 43%, not the 21%.

Farmer Organizations have proved that the collective efforts not only improve the water distribution equity among water users and ensure tail reach supply but have significantly reduced the maintenance cost and completion of work in time. This all has achieved because of capacity building of the water users. If, water is reliably supplied to the water users then application efficiency will significantly improved in future.

REFERENCES

Kijne D. Murray-Rust and W. Snellen (2002), A challenge program on water and food: Ensuring food security via improvement in crop water productivity. International Water Management Institute (IWMI), Sri Lanka.

Perry C.J. (2001), Charging for Irrigation Water: Issues and Options. With the Case Study from Iran, Research Report 52, International Water Management Institute, (IWMI), SriLanka.

Habib Zaigham and Marcel Kuper (1998), Performance assessment of the water regulation and distribution system in the Chishtian subdivision at the main and secondary canal levels. IIMI, Pakistan National Programme, Report No R-59, July, 110 pp.

Stosser (1997), Farmers action and improvement in irrigation performance below the mogha: How farmer manages scarcity and abundance in a large-scale irrigation system in southeast Punjab; Pakistan. International Water Management Institute (IWMI), Pakistan.

J. F. Alfaro and J. Marin (1996), Water and energy use for irrigation in Latin America.

Perry Chris, J. (1996) "Qualification and Measurements of a Minimum set of a Indicators of the Performance of Irrigation systems". International Irrigation Management Institute (IWMI), Colombo.

Bhutta M.N. and Vander Velde (1992),"Equity of Water Distribution along Secondary Canals in the Punjab, Pakistan". Irrigation and Irrigation Systems. Vol.6. No.2, pp: 161-77.

GROUND WATER MITIGATION IN THE DESCHUTES BASIN OF CENTRAL OREGON

Herbert G. Blank[1]
Kyle G. Gorman[2]

ABSTRACT

During the early 1990s, the Oregon Water Resources Department (OWRD) determined that due to concerns about interaction with surface water it had inadequate information on which to base further issuance of ground water permits. Since surface waters were fully appropriated many years ago, any new water uses must be met from ground water. An OWRD and United States Geologic Survey (USGS) study concluded that surface and ground water were hydraulically connected in the basin and that ground water was a significant component of the base flow of the Deschutes River, particularly in the late summer. On the basis of this knowledge, OWRD ceased issuance of further ground water appropriations due to State scenic waterway protection violations. This paper examines the background and subsequent actions taken to develop rules by which groundwater permits could be issued providing that actions are undertaken to mitigate or offset the impacts of new development. Through a working group process with consultation from concerned parties, OWRD developed mitigation rules which detailed procedures and introduced the concepts of mitigation credits and mitigation banking. This paper details the more than ten-year effort to resolve issues of water reallocation in the basin from the perspective of water users, development interests, environmental groups and water management agencies.

BACKGROUND

The Deschutes Basin, located in central Oregon, is a high growth area, attracting new residents and tourists due to favorable climate and the wide range of opportunities for outdoor recreation. The region's population growth rate, which is the highest in the state, means changing and potentially growing demands for water (Blank and Johnson, 2004). Since all surface waters were appropriated many years ago, any new water uses must come from ground water. In the early 1990s, the Oregon Water Resources Department (OWRD) realized that it had very little quantitative information about the groundwater hydrology of the upper Deschutes Basin and that it did not have a good basis for making decisions about issuing new ground water permits.

[1] Consultant, Bend, Oregon; e-mail: hblank@yahoo.com
[2] Oregon Water Resources Department, Bend, Oregon

In order to better understand the hydrology of the Deschutes Basin, the OWRD, local cities, counties and the Confederated Tribes of the Warm Springs began a cooperative study with the United States Geological Survey (USGS) in 1993. This extensive study of the region's groundwater was published in 2001 (Gannett, et al, 2001). The study found that the region's rock layers consisted of highly fractured basalt mixed with permeable volcanoclastic material of relatively recent origin, which is underlain by older impermeable rock layers. Rivers have incised the permeable layer down to the underlying impermeable layer. A water table map shows the convergence of the three rivers (Deschutes, Crooked and Metolius) coincides with the outflow of numerous springs which return groundwater to the rivers. Recent studies have shown a short time lag between precipitation and snowmelt and water level response in wells located on the east slopes of the Cascade Mountains, indicating a very direct connection between surface and ground water.

OREGON RIVER PROTECTION LEGISLATION

Three key laws protect Oregon's rivers and the Deschutes River in particular. The Oregon State Scenic Waterway Act was adopted by a ballot initiative in 1970. The Act declares that the "highest and best use of the waters within a scenic waterway are recreation, fish and wildlife uses." The law is intended to protect rivers from any further reductions in flows. The Act designated the Lower Deschutes River from Pelton Dam to the confluence with the Columbia River as Scenic Waterways. Other reaches gained protection under the Act in the late 1980s. Although the Act protects rivers from further reductions in flows it does not restore or reallocate flows.

The Instream Water Rights Act was adopted by the State legislature in 1987. The law allows water flowing in a river to be protected by an "instream water right," a right which has equal standing to other water rights. In 1988, the Oregon Supreme Court, in Diack v. City of Portland, interpreted the Scenic Waterway Act to mean that "no diversion of water that otherwise would enter a scenic waterway may be permitted unless the requirement of the Act are met." Under this ruling the Oregon Water Resources Department (OWRD) was required to determine that scenic waterway flows will not be impaired before issuing new water rights.

In 1995, the State legislature passed Senate Bill 1033 which authorized reasonable and appropriate uses of ground water while not jeopardizing flow protection for State Scenic Waterways. The OWRD was required to review ground water applications and make a finding as to whether proposed use will "measurably reduce" the flows necessary to maintain free flowing character of a scenic waterway in quantities necessary for recreation, fish and wildlife. "Measurably reduce" was defined as individually or cumulatively reducing steamflow by 1 percent of average daily flow, or 1 cubic foot per second (cfs), whichever is less. The statute requires that permits include the condition that they be regulated if the "measurably reduce" standard is triggered and requires mitigation by new ground water applicants once the measurably reduce standard is triggered. The legislation also introduced the concept of "mitigation," allowing for new ground water uses, provided the projected impacts are offset or mitigated.

PROVISIONAL PERMITS AND PERMIT BAN

Preliminary results of the USGS study, obtained in 1998, showed that ground water originating in or flowing through the Upper Deschutes Basin discharges into the lower reaches of the Deschutes, Metolius and Crooked Rivers above and within Lake Billy Chinook. Based on these initial study results, OWRD staff determined that ground water use in the Basin has the potential for substantial interference with surface water and the "measurably reduce" standard described in the previous section is triggered.

From 1995, all new ground water rights issued within the Deschutes Basin included the condition that allows for future curtailment of ground water use if and when data are available which demonstrate an adverse impact on the Scenic Waterway. During this period 165 such permits were issued, representing a flow of 207 cfs (OWRD, 1998). As of 1998, based on the preliminary USGS study results, new ground water applications were put on hold. As a result, a backlog of 125 permit applications was built up. Included in this backlog were applications for major resort developments which could have major economic impact on the region. In order to resolve this issue, the Department convened a group of stakeholders to develop mitigation strategies intended to offset impacts on the Lower Deschutes while accommodating new uses in the upper basin.

PUBLIC RULEMAKING PROCESS

After an initial series of townhall-type meetings in 1998, the OWRD convened a working group to develop a long-term ground water mitigation strategy which was to guide the making of ground water mitigation rules. A Memorandum of Understanding was drafted at the onset of the process and finalized in April 1999, with over 40 parties signing representing irrigators, irrigation districts, local government, interest groups, private and municipal water providers and development interests (Pagel, 1999). The Memorandum of Understanding (MOU) established a steering committee of about 20 members who were chosen to provide guidance for the process and a facilitator, hired by a local water supply company, assisted with meeting management. The MOU set a target date of September 2000, for the completion of a water management plan for the Deschutes Basin, which would contain strategies for meeting water demands "...avoiding any impacts or injury to surface water flows which may occur or by establishing adequate and appropriate mitigation."

The steering committee met about monthly, and although they made substantial progress, they did not reach full agreement on proposed recommendations. Early in the process the working group debated over the definition of “mitigation” (Pagel, 2002). Environmental groups argued for a “bucket-for-bucket” replacement as the allowable type of mitigation, whereas others argued for upland-based watershed restoration activities as allowable mitigation. The working group reached consensus that mitigation, at least initially must consist of “wet” water, i.e., legally protected for instream use, although the group indicated a willingness to review this issue once a long-term watershed restoration plan is developed.

A major debate of the steering committee was whether canal lining and piping, as well as groundwater recharge projects, were legitimate mitigation measures to offset the impacts of new ground water development. Environmental representatives argued that such measures were “robbing Peter to pay Paul.” Although conservation measures would result in benefits in the Middle Deschutes in terms of restoring flow, they could result in downstream flow reductions, since, as the USGS study found, the basin is closed and any water “lost” from canals would show up as surface water in the lower river and conversely any reduction in seepage water from a canal would result in lower flows downstream. Thus, they argued, conservation measures should not qualify as mitigation measures, since these measures, in essence, “transfer” the lost water from canals to the river, but do not “create” any water which could be used for mitigation of new ground water development. On the other hand, the Department argued that there was a strong legislative mandate through the Conserved Water Act (Blank, et al 2004) to encourage efficiency improvements notwithstanding any potential reduction in recharge.

The result of the two-year rulemaking process was the preparation of a draft Ground Water Mitigation Strategy. The purpose of the Strategy was to ensure compliance with the State Scenic Waterway Law and protect existing senior surface water rights while accommodating appropriate future ground water development in the basin. The Strategy was intended to serve as a road map for the Department and for the public in understanding the potential impacts of ground water development, and providing appropriate mitigation to offset those impacts. The Strategy was also intended to serve as the basis for administrative rules to be developed by the OWRD.

The OWRD Director, Martha Pagel, had been closely involved in the consultative process and had personally attended many meetings in Bend. Her successor, Paul Cleary, who took over from her in July, 2000, indicated a desire to get on with the issuance of the rules. A meeting was held in June 2001, at which Mr. Cleary indicated a desire to “...wrap discussion of comments and the Department's response to those comments into the discussion of the Mitigation Rules, the main focus of the meeting” (Deschutes Steering Committee, 2001).

Despite major disagreements over the two points relating to conservation and recharge projects, an OWRD staff lawyer was called upon to draft the rules based on input from the stakeholder group and several public meetings in which the draft rules were presented. Initial draft rules were issued in September, 2001, and more than 100 written comments were received. Revised rules were issued in the Spring of 2002, which generated similar controversy. Despite the lack of agreement, the rules were issued.

DETAILS OF THE RULES

The final rules provide that OWRD may only approve new ground water permits in the Deschutes Ground Water Study Area if mitigation is provided. The general sense of mitigation is the return of water (i.e. what had been consumed, usually in the production of irrigated crops) to the river to offset the new ground water being provided. A mitigation obligation may be satisfied by: (a) the transfer of an existing water right to an instream use; (b) a permit to appropriate water for artificial recharge; (c) a secondary permit to use stored water from an existing reservoir; or, (d) the allocation of conserved water where the applicant's portion of the conserved water is allocated for instream use. Mitigation water must be provided within the zone of impact of the new use, must be legally protected for instream use, and be committed for the life of the permit. The amount to be mitigated is equal to the amount of consumptive use of the proposed ground water use, as determined by the OWRD. If an applicant provides evidence that the ground water appropriation does not have the potential for substantial interference with surface water rights and will not measurably reduce scenic waterway flows, the OWRD shall not require mitigation for that specific ground water use.

The final rules provide for the issuance of up to 200 cfs of new ground water rights. When the level of permits reaches 150 cfs or prior to January 1, 2008, the rules are to be evaluated to determine whether the restriction shall be lifted. This decision to lift the limit is to be made only if Scenic Waterway flows and instream water right flows continue to be met at equal or above historic levels. Additionally, annual monitoring is to occur of streamflow data, information on new ground water appropriations and mitigation activity. The final version of the rules considerably simplified earlier versions by excluding the group of conditional ground water permit holders (those issued permits from 1995 through 1998) from mitigation requirements.

The final rules were submitted for approval by the director of OWRD to the Oregon Water Resources Commission in 2002. The memo transmitting the request (Cleary, 2002) did not specifically address the issue of double counting caused by water conservation (i.e. piping) projects. Over 160 written comments and oral testimony were submitted on the April 2002 hearing draft. An annex included a summary of thirteen of these issues. The last of these was that "Canal lining and piping should not be treated as a form of mitigation. This is a restoration activity only because it does not add any new water to the system and just moves water around." No further discussion of this issue was included in the memo.

THE COURT CASE

In September of 2002, the Oregon Water Resources Commission adopted the new groundwater mitigation rules and they were subsequently published as Oregon Administration Rule (OAR) 690-505-0600. Shortly thereafter (November, 2002) Waterwatch (an Oregon non-profit river conservation organization) and others filed a court case against the Oregon Water Resources Commission, arguing that the mitigation rules violated the Scenic Rivers Act. The plaintiffs argued that the rules did not meet the requirements of the Scenic Rivers Act which requires "maintaining the free-flowing character of waters in the designated scenic waterways in quantities necessary for recreation, fish and wildlife." Secondly, that the rules "overallocate surface waters in the basin" and will not protect existing instream rights because the standard for 'mitigation' does not protect instream water rights from diminishment."

The court of appeals finally ruled in favor of Waterwatch in May 2005, determining that the mitigation rules were invalid. The ruling (Court of Appeals, 2005) did not directly address the crux of the disagreement, that, in the cases of conservation projects (i.e. piping or lining of canals) the rules allow for double counting. Rather, the court ruling concentrated on the definition of the terms "mitigation," "moderation" and "maintenance." The court ruled that the state law requires "maintenance" of the flows while the rules only require "moderation" of the impacts on the flows. Although the definition of "mitigation" is to lessen or "moderate" the effect of a negative action, in this case the law requires maintaining the current level of flow. The judicial ruling stated that since the rules do not accomplish this objective, they are rejected. The judicial review also rejected side issues related to standing and experimentation.

The judicial review included a caveat that was shortly to become significant. The judicial review stated, "We recognize that the question of the appropriate balance between the protection and use of the resources at issues here is a policy decision that is appropriately made by the legislature... If the legislature should choose to alter the policy presently embodied in the statutes, it is free to do so." The ruling continues, " In sum, (the law) requires the maintenance of stream flows in quantities that the commission has established as necessary for fish, wildlife and recreation. The rules at issue in this case require only the moderation of impacts on those flows... Additionally, because the agency does not know how and when a ground water appropriation will impact stream flows, the rules do not provide a mechanism to sufficiently ensure the statutory objective is met."

LEGISLATIVE ACTION

Following the judicial ruling, the Oregon legislature took up the case in 2005 and within a two-month period passed and signed a bill, HB 3494, which put the rules back in force, essentially in the same form as proposed, but with a “sunset” provision that expires January 2, 2014. The bill was proposed by two local representatives in a session which included several other pieces of water related legislation which languished and died.

Martha Pagel, the former director of OWRD testified in favor of the legislation. She argued (Pagel, 2005) that the program reflected the original intent of SB 1033 and offered unprecedented benefits to the Deschutes River. She stated that the concepts embodied in the rules work, and she also cited the extensive public and legislative involvement in the development of the rules. “Yet, even though complete consensus is not always possible; public involvement and accountability can offer a reasonable alternative for moving forward.”

Although the double counting from piping projects was incorporated in the legislation, it is still to be determined whether this provision will come into play. The first aspect is financial. To date, there has been no lining or piping of canals in the Deschutes basin for the intent of mitigation. Some estimates put the cost of piping greater than the cost of purchasing individual water rights (Deschutes Groundwater Steering Committee, 2000). The Conserved Water Act provided incentives for lining by allowing at least 75% of water savings to be made available to users, while the remaining savings would be returned to the river. The current rules would presumably shift the financing to new water users, in that they would finance any lining and then make use of the water saved. Secondly, the threat of further lawsuits still exists. Although the law now provides for mitigation credits in exchange for conserving water, such as through pipelines, this provision is still to be tested. The Bend City Attorney, as quoted in the local newspaper (Bend Bulletin, Mar. 13, 2006), stated that if the city were to invest money to pipe a canal, it also has to consider legal challenges and that there have been no conserved water projects to date which have resulted in mitigation credits and the right to drill a new well.

CASE STUDY: DESTINATION RESORTS

Outside of municipalities the largest growing sector of consumptive water use in the Deschutes Basin is destination resorts. These are vacation and recreation sites which incorporate golf courses, homes and short-term vacation rentals. The first major destination resort in Central Oregon, developed in the late 1960s, was Sunriver. Since then major resorts include Black Butte, Eagle Crest, Brasada Ranch and Pronghorn. Currently in the planning stage is Thornburgh Resort. In addition to destination resorts there are other golf course developments, both private and public. There are currently more than a twenty golf courses in the Deschutes Basin.

Generally speaking, large-landscape water budgets including golf courses will consume approximately 80% of the reference evapotranspiration (Green, 2005). The reference evapotranspiration (ET_o) in Bend for the summer season (mid-April through mid October) is 34.4 inches (Bureau of Reclamation, 2006). Awbrey Glen Golf Course in Bend recently installed a new irrigation system and reduced their water usage from an average of 94 million gallons per season (mid April to mid October) to 77 million gallons per season in 2005. Although this usage occurred in a year with above-average rainfall (7.31 inches versus an average of 3.63 inches reported in Redmond over the 6-month period) (NOAA, 2006), this equates to a seasonal water use over the 110 irrigated acres of 25.8 inches or 75% of the reference ET_o. This compares to the diversion water duties of many irrigated farms in the region of 9 feet or more. Thus, although golf courses are high water users, in general they can be fairly efficient users, particularly in comparison to typical irrigated farms.

Earlier destination resort developments were able to obtain ground water permits through the normal OWRD process. The third phase of Eagle Crest was being developed at the time of the mitigation process. The Eagle Crest III ground water application was filed in October 1998, during the moratorium on issuance of ground water permits. The application requested 1500 gallons per minute (gpm) although the average diversion at full build-out was estimated at 200 gpm (Walker, 2000). The developers filed a mitigation plan which included lease and eventual purchase of 180 acres of Swalley Irrigation District water rights and dedication of these rights to in-stream use as mitigation for ground water development. The mitigation plan was considered a pilot project and was presented to the Deschutes Basin Task Force by Martha Pagel in a meeting on February 15, 2000. There were no further comments on the proposal at that time, the Proposed Final Order was issued by OWRD that day and went into effect after a period of public comment. Eventually 21 acres was transferred instream as mitigation for ground water development

Pronghorn resort avoided the problem of mitigation by buying treated Level IV wastewater from the Bend wastewater treatment plant. Currently one golf course is operational and a second is being developed. OWRD staff have confirmed that Pronghorn's March through October use in 2005 for the one course and all associated irrigated ground and water features was 260.5 acre-feet. Based on 125 acres of land irrigated, the use was 25 inches per acre irrigated per season.

Brasada Ranch is a destination resort still in the development stage. The golf course is designed to maximize native vegetation, with only 60 acres planted to irrigated turf, compared to a usual 110 acres. The back nine holes were recently planted and the front will be planted this season. The irrigation system will be state-of-the-art, using a satellite system to monitor conditions and control sprinklers. Brasada is a patron of Central Oregon Irrigation District, and as such it will make use of surface rights transferred from formerly irrigated acreage within the irrigation district. Limited ground water rights and supplies from a private water company will provide the domestic water supply for the development.

Thornburgh Resort is the first resort to be developed since the reinstatement of the mitigation rules. The developers plan to mitigate for new ground water use by acquiring water rights from a large landowner. The resort, to be built on nearly 2000 acres, will at full build-out include 1000 homes, condos, 500 hotel rooms, three 18-hole golf courses, and a 20-acre lake (Source, 2005). The announced plan is to transfer surface water rights currently used for irrigation to instream use. This will be a "bucket for bucket" transfer with surface water being transferred to the river in exchange for mitigation credits which allow issuance of a ground water right. Such a transfer would not have been allowable without the mitigation rules, although this case is similar to the Eagle Crest III precedent. Even though this is a straight forward exchange, there are still unresolved questions relating to seasonal withdrawals – surface water rights are generally restricted to the irrigation season, whereas in this case the usage may be considered quasi-municipal, allowing for year-round use. Although the mitigation rules may appear to be settled presently, the case for various planned conserved water (pipeline) projects may still only be settled in the courts.

CONCLUSIONS/IMPLICATIONS

The more than ten-year process, from the identification of the problem to implementation of rules, is surely one not to be emulated. Issuance of rules without regard to the lack of consensus within the consultative process led to a loss of two and a half years in the judicial process. The rapid legislative process, which if not passed in 2005, would have added two years to the process since the Oregon legislature only meets every two years. Change in leadership at OWRD during the consultative process may have been a factor in not reaching consensus. Other factors, such as the effectiveness of the facilitation, may have contributed. Looking back at the meeting notes at this time, there seems to have been a lack of focus in those meetings. Had the meetings focused (and reached consensus) early on on the key issue of whether conservation projects should be considered as mitigation one speculates that the process could have been completed in a more timely manner.

Due to the changing nature of the region, irrigated agriculture is no longer viewed with the priority it once had. Increasingly, water rights are used on pasture for horses and to support other "lifestyle" water uses rather than to support income generation activities once associated with irrigation (Skaggs and Samani, 2005, Aylward, 2006). Yet legislators are not willing to directly address the political opposition which would ensue from major revisions of water rights legislation. As the Deschutes case demonstrates, though, legislators are willing to work around the edges, passing legislation which attempts to smooth the mechanism for transferring water to new uses. Restoration of flow in the middle Deschutes River is viewed as a high priority and measures which accomplish this tend to be viewed favorably by legislators and their constituents, although any attempt to take water from irrigators is not. Unfortunately, the newly enacted legislation includes some controversial provisions, which were not agreed to by all the parties involved in the process, and these unresolved issues may hinder future transfers.

REFERENCES

Aylward, B. "Growth, Urbanization and Land Use Change: Impacts on Agriculture and Irrigation Districts in Central Oregon" Water Summit Draft, Deschutes Water Alliance, May, 2006.

Bend Bulletin, Mar. 13, 2006, "Bend Could Back Out on Deal to Pipe Main Canal" by Christine Metz.

Blank, Herbert G., Kyle G. Gorman and Laura Meadors, "Meeting Changing Water Demands in the Deschutes Basin of Central Oregon" United States Committee on Irrigation and Drainage Water Rights and Related Water Supply Issues October 13-16, 2004, Salt Lake City, Utah.

Blank, Herbert G., Stephen C. Johnson, "Managing Changing Water Demands In The Central Oregon Irrigation District" Proceedings Third International Conference on Irrigation and Drainage, United States Committee on Irrigation and Drainage, San Diego, California 2005.

Bureau of Reclamation, "Agrimet Monthly Average Reference ET, http://www.usbr.gov/pn/agrimet/monthlyet.html, 2006.

Cleary, Paul R., Memo to Water Resources Commission, Subject: Water Resources Commission Meeting, Request for Adoption of Administrative Rules, OAR Chapter 690, Division 505 – Modifications to Deschutes Basin Program (Deschutes Basin Ground Water Mitigation Rules) – and OAR Chapter 690, Division 521 – Deschutes Basin Mitigation Bank and Mitigation Credit Rules, September 13, 2002.

Court of Appeals of the State of Oregon, May 18, 2005. Waterwatch of Oregon et al v. Water resources Commission, Judicial Review. http://www.publications.ojd.state.or.us/A119779.htm

Deschutes Water Management Steering Committee, “Meeting Notes” http://www1.wrd.state.or.us/files/Publications/Notices/deschutes-sum/71_062701.meetingnotes.html, June 28, 2001.

Deschutes Groundwater Steering Committee, “Report on Evaluation of Basin Infrastructure Alternatives for Streamflow Enhancement” January 18, 2000.

Green, Robert L., “Trends in Golf Course Water Use and Regulation in California” http://ucrturf.ucr.edu, August, 2005.

Gannett, M. W., K. E. Lite Jr., D. S. Morgan and C. A. Collins, “Ground-Water Hydrology of the Upper Deschutes Basin, Oregon,” Water Resources Investigations Report 00-4162, United States Geological Survey, Portland, 2001.

NOAA, National Weather Service Portland, Oregon, “Observed Weather Reports” http://www.weather.gov/climate/index.php?wfo=pqr, 2006

Oregon Water Resources Department, “Water Development Issues in the Deschutes Basin,” http://www1.wrd.state.or.us/files/Publications/Notices/deschutes-announce/98_background.html, October 13, 1998.

Pagel, Martha O. “Memorandum to Water Resources Commission Deschutes Water Management Plan Update, Agenda Item H,” November 10, 1999.

Pagel, Martha O., “Creative Programs and Projects to Increase Water Supply Mitigation and Mitigation Banking: Strategies for Meeting New Supply Needs in Oregon’s Deschutes Basin. University of Denver Water Law Review,” Volume 6, Issue 1, Fall 2002.

Pagel, Martha O., Before the Senate Rules Committee, Testimony on HB 3494, July 6, 2005.

Source Weekly Newspaper, “Showdown in Tumalo” by H. Bruce Miller Volume 9 Issue 29 July 21, 2005.

Skaggs, Rhonda and Zohrab Samani, “The Changing Face of Western Irrigated Agriculture: Structure, Water Management and Policy Implications” Proceedings Third International Conference on Irrigation and Drainage, United States Committee on Irrigation and Drainage, San Diego, California, 2005.

Walker, Thomas A. “Meeting Notes: Pending Groundwater Appropriation Application” January 31, 2000.

GROUNDWATER MANAGEMENT IMPROVEMENTS TO MITIGATE DECLINING GROUNDWATER LEVELS — A CASE STUDY

Brian Sauer[1]
Dan Temple[2]

ABSTRACT

The A&B Irrigation District in south-central Idaho supplies water to irrigate over 76,000 acres. The district's 14,660-acre Unit A is supplied with water from the Snake River. Unit B is comprised of 62,140 acres of land irrigated by pumping groundwater from the Eastern Snake Plain Aquifer (ESPA) using 177 deep wells. Pumping depths range from 200 to 350 feet. Water from Unit B wells is distributed to irrigated lands via a system of short, unlined lateral canals averaging about 3/4-mile in length with capacities of 2 to 12 cfs.

During the period from 1975 to 2005, the average level of the ESPA under the A&B Irrigation District dropped 25 ft and as much as 40 ft in some locations. This has forced the district to deepen some existing wells and drill several new wells. To help mitigate the declining aquifer, the district and its farmers have implemented a variety of irrigation system and management improvements. Improvements have involved a concerted effort by the district, landowners, and local and federal resource agencies.

The district has installed variable speed drives on some supply wells, installed a SCADA system to remotely monitor and control well pumps, and piped portions of the open distribution laterals. This has permitted farmers to connect farm pressure pumps directly to supply well outlets. Farmers have helped by converting many of their surface irrigation application systems to sprinklers, moving farm deliveries to central locations to reduce conveyance losses, and installing systems to reclaim irrigation spills and return flows.

INTRODUCTION

The Eastern Snake Plain Aquifer

The Snake River Plain is an extensive, crescent-shaped lowland that extends from near the western boundary of Yellowstone National Park in eastern Idaho to the

[1] Hydraulic Engineer, U.S. Bureau of Reclamation, Snake River Area Office, 230 Collins Road, Boise, ID 83702. e-mail: bsauer@pn.usbr.gov

[2] Manager, A&B Irrigation District, P.O. Box 675, Rupert, ID 83350

Idaho-Oregon border where the Snake River enters Hells Canyon. The area is drained by the Snake River and its tributaries. The source of the Snake River water is snowmelt from the winter snow pack in the surrounding mountains. Most the runoff occurs in the early spring before the irrigation season begins, so the water must be stored until it is needed later in the summer. The Snake River above King Hill has an extensive reservoir system with a storage capacity of about 5.5 million acre-ft.

A large regional aquifer system underlies the Snake River Plain (Fig. 1). Abrupt changes in hydrogeologic conditions along the Snake River between Salmon Falls Creek and King Hill, Idaho, serves as the dividing line between the Eastern and Western portions of the aquifer. The Eastern Snake Plain Aquifer (ESPA) is perhaps the single-most important aquifer in Idaho. Springs from the ESPA are also a major source of water for the Snake River. The eastern Snake River Plain is about 170 mi long, 60 mi wide, and covers 10,800 square miles. The plain extends from Mud Lake in the northeast to King Hill in the southwest. The ESPA is composed mostly of basalt which is over 3,000 ft thick in the center of the plain and only a few hundred feet along the margins. Total groundwater storage in the aquifer is estimated at 200- to 300 million acre-feet, roughly the equivalent of Lake Erie. Most agricultural soils are the sediments along the Snake River at the margins of the plain. The aquifer supplies water for irrigated agriculture, cities, and aquaculture.

Much of the discharge from the ESPA is through springs. Two major spring discharge areas are near the American Falls Reservoir and the Thousand Springs area near Twin Falls, Idaho. From Milner Dam to King Hill, the Snake River is entrenched in a steep basalt canyon as much as 700 feet deep. Spring flow from the north side of the canyon along with a few streams from the south rebuilds the flow in the Snake River below Milner Dam. There are several large springs along the canyon with average flow rates of 200 cubic feet per second and 400 cubic feet per second.

Surface water applied to irrigated lands above the aquifer is the largest source of aquifer recharge. Annually, this amounts to about 60% of the total recharge. As irrigation practices and technologies have improved, recharge has been reduced. Also, withdrawals from the aquifer for irrigation and other uses have increased over time. Aquifer levels have declined and have impacted all ESPA water users. Recent drought years have reduced surface water supplies for irrigation above the ESPA and have also increased groundwater pumping to supplement surface water supplies. This has resulted in further depletions of the aquifer.

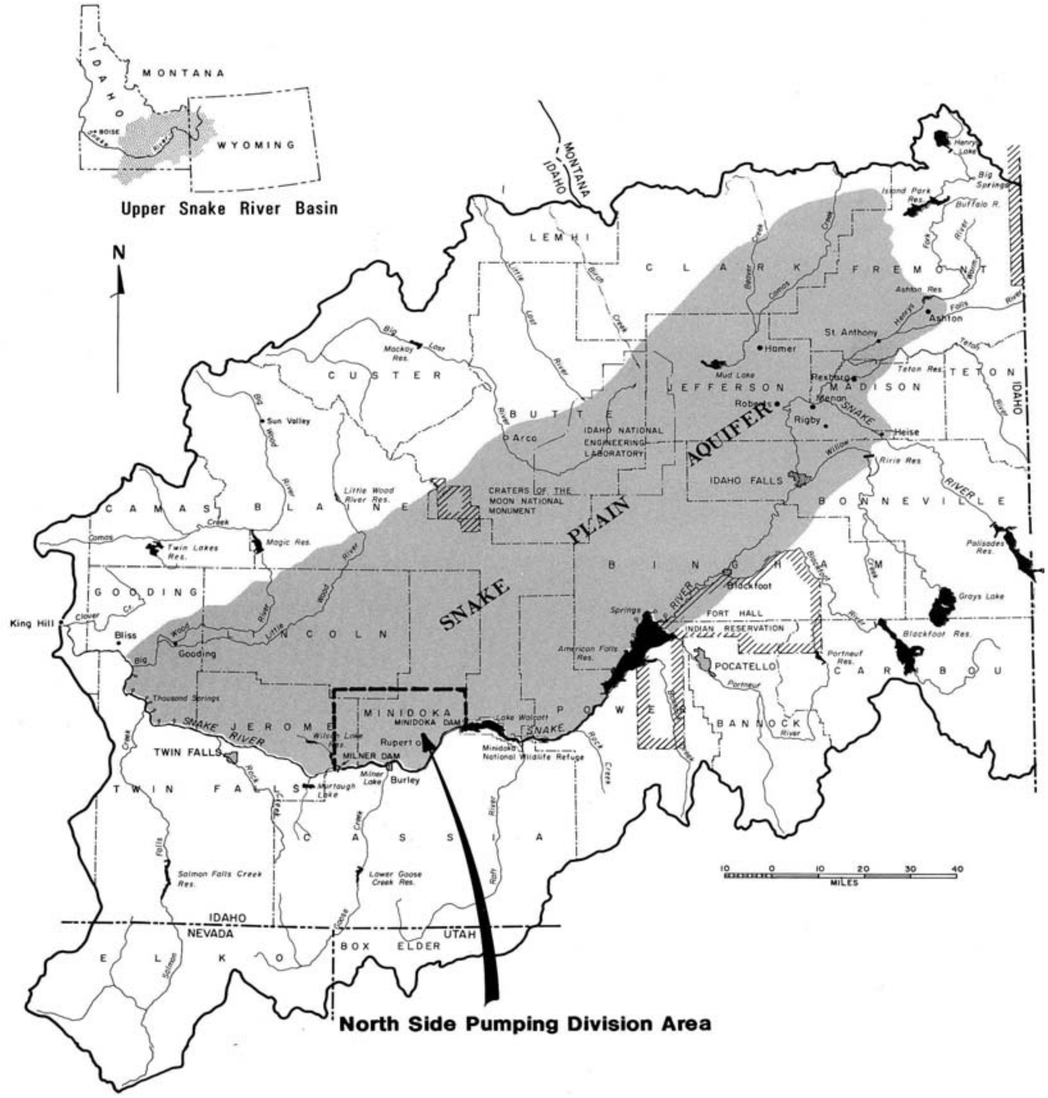

Figure 1. Location of Eastern Snake Plain Aquifer and A&B Irrigation District

As a result of the incidental recharge from surface water irrigation over the ESPA, about 70% of the flow at King Hill is now ground water discharge from the Thousand Springs. Records indicate spring flow in the Milner Dam to King Hill reach of the Snake River increased from 4,200 cfs in 1900 to 6,800 cfs in 1950. Spring flows have recently declined to less than 6,000 cfs or about 4,800,000 acre-feet per year. The cause for this decline is a combination of the reduction in incidental recharge from surface water as a result of the conversion from flood to sprinkler irrigation, and extended drought and groundwater pumping.

A&B Irrigation District

The A&B Irrigation District operates and maintains the Northside Pumping Division of the Minidoka Federal Reclamation Project. The Northside Pumping Division, located in Minidoka and Jerome Counties in south-central Idaho, was authorized by Congress in 1950. The project area is relatively compact, ranging from 2 to 7 miles in width and about 30 miles in length. Construction of the project was completed in 1959. Nearly 695 new farm units were made available for settlement within the District, almost all for homestead entry. Under the prevailing law, veterans of World War II and the Korean Conflict had preference in acquiring the new farm units.

The district contains approximately 76,800 irrigated acres, split between the 14660-acre A Unit which receives up to 270 cfs of natural flow and reservoir storage pumped from the Snake River, and the B Unit, which uses 177 deep well pumps, with a combined capacity of about 1100 cfs. The A Unit has a 5-pump plant which lifts water approximately 168 ft into a gravity distribution system of approximately 50 miles of unlined canals and laterals.

In the B Unit, water is carried from the supply wells to farms via a system of short, unlined lateral canals averaging about 3/4-mile in length with capacities of 2 to 12 cfs. Pumping depths range from 200 to 350 feet. Generally, one or two single-speed deep well pumps discharge into an open pond. The ponds have one or more gates which control deliveries to individual farms or to a lateral which serves several downstream farm deliveries. Valves at the well head regulate outflows. Mismatches between well output and irrigation deliveries are spilled into project drains or sumps.

Since the inception of the project, the District's annual farm delivery rate has remained relatively steady at approximately 3 acre-feet/acre. Soils are generally well-drained sandy or silt loams with underlying fractured basalt. Major crops include sugar beets, wheat, barley, malting barley, potatoes, and alfalfa hay.

The project originally included 370 miles of unlined, open drains, several drain water relift pumps, and 78 injections wells that discharged drain water into the fractured basalt Eastern Snake Plain Aquifer that underlies the District. In order to reduce pumping costs and to help alleviate water quality concerns, additional relift pumps and pipelines were installed in the district. The district has abandoned 62 injection wells and capped 5 others to potentially be used as future production wells.

The declining aquifer under the District has had very significant impacts on the A&B Irrigation District. The average pumping depth of the B Unit wells has dropped nearly 25 feet since the mid-1970's. There have been short periods of recovery during years with above-average precipitation, but these recoveries have been outweighed by drought cycles during the late 1970's, the early 1990's and the 1999-2004 period. Figure 2 shows a graph of the average pumping depth for all district supply wells since the inception of the district.

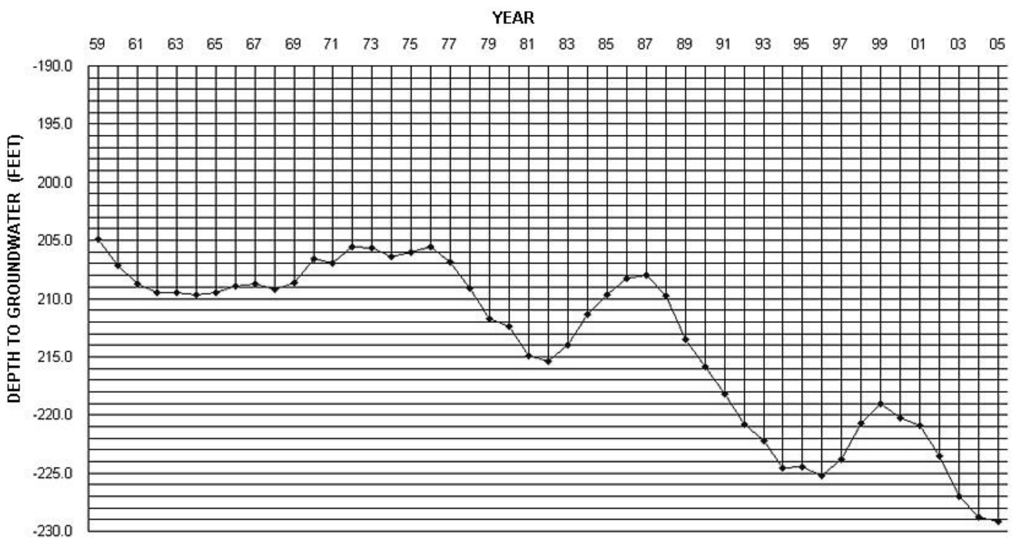

Figure 2. Average Depth to Groundwater by Year

Declining aquifer levels have increased the pumping costs and reduced well outputs. Since 1987, the district has deepened 30 wells in an attempt to regain some of the capacity lost as a result of the declining aquifer. Dozens of other well pumps have been replaced or fitted with new impellers to increase pumping head. In the western part of the district, 5 supply wells have been temporarily abandoned and 4 new wells have been drilled. In some cases, surface water from the A Unit is pumped to lands originally served by B Unit groundwater wells.

As supplies have declined, farmers in the district have improved efficiencies by converting their farm irrigation systems from surface applications to sprinklers. This helps to reduce overall water use, but also adds additional costs for pressurizing the farm systems. When coupled with low commodity prices, the increasing pumping costs and cost of application system modifications, many farms in the district are experiencing financial difficulties.

GROUNDWATER MANAGEMENT IMPROVEMENTS

A& B Irrigation District and its water users have undertaken many efforts to mitigate the impacts of the declining ESPA. These have involved a variety of equipment and management improvements. Many of the improvements have been made to improve the flexibility of both the farm application systems and the district supply systems.

SCADA

Beginning in 1998, A&B began a program to install industrial electronic controllers and radio telemetry on its irrigation supply wells to remotely control and monitor the operation. Historically, the District required 24-hour advanced scheduling of water deliveries, and pumps were operated by District staff during regular work hours. The 24-hour delivery schedule didn't necessarily coincide with actual farm irrigation schedules, wasting water and electricity.

The automated system allows the District to start and stop pumps remotely from District offices. Office personnel and on-call operators at remote locations can program starting and stopping times for individual pumps or pump systems. For example, if an irrigator anticipates completion of his irrigation cycle during the night, he can inform the District office of the time to shut off the pumps and the shut-off can be entered into the central control computer the day before. When the pump is shut off, water that is not needed for irrigation stays in the aquifer.

The SCADA system also permits District staff to monitor the performance of individual pumps in the system, including flows, power consumption, and bearing temperatures on a graphical display. Remote operation also saves staff time and pickup miles for routine water changes. This is especially valuable when it is necessary to start several pumps after power outages. The SCADA system also provides alarm notifications and call-outs for specified conditions.

Currently, 47 of the District's 200 pumps are connected into the SCADA system. The system is PC-based and provides radio and phone call-outs. The remote sites use Allen-Bradley RTU's with a variety of sensors. Communication is accomplished using a 5-watt radio network. The SCADA system is also used to monitor (but not operate) the district's A-Unit pumping plant.

Reducing or Reclaiming Lateral Losses

Since most of the District's groundwater was distributed to farm deliveries via open laterals, there were inevitable mismatches between the pumped water supply and the farm deliveries. In the early days of the district, all lands were irrigated by surface methods, which resulted in relatively continuous farm deliveries. But as more farms converted to sprinkler irrigation, farm water use became more variable and there were increases in spills from the conveyance system.

The District has used several methods to help reduce conveyance losses in laterals. In several locations where farm pumps are located near supply wells, A&B has permitted a direct connection from the well pump discharge to the farm pump inlet. Regulating valves and flow meters are installed between the well head and the farm pumps to measure and regulate the farm deliveries. Most of these valves and flow meters are connected into the district SCADA system.

In instances where new sprinkler systems are being installed, the District encourages farmers to locate their farm pressure pumps near the district's wells. Water is then conveyed by buried pipeline to the sprinkler system. The open delivery lateral can then be eliminated, which helps landowners "square up" fields and eliminate obstacles. Also, by locating farm pumps near the District's wells, landowners can take advantage of the close proximity of electric power for their pressure pumps and reduce the costs of their new electric service.

In location, several farmers have installed farm pumps on a jointly constructed storage and regulating pond. By having their water delivered to a larger pond, they have a more constant supply, they have more flexible farm system operation, and the pond catches most operational spills. A water level sensor on the pond is connected to the supply well through the district's SCADA system to shut off the well pump if the pond gets too full. A&B has also constructed two wetland sites at the end of the D and F Drains. These sites collect farm runoff, improve drain water quality and reuse the collected water for agricultural irrigation.

Variable Speed Pump Drives

A&B has installed variable speed drives on 8 supply wells to better match water supplies with the irrigation and reduce total pumping. Four wells have Variable Frequency Drives (VFD) which electronically adjust the frequency of the alternating supply current to set the speed of the electrical drive motor (Fig. 3). The outlet pipes of the wells equipped with VFD's are connected directly to the inlet of farm booster pumps.

The well pump inlets are equipped with pressure transducers and the farm pump outlets are equipped with propeller flow meters. Both pressure transducers and have electronic outputs, and flow and pressure information is read by the SCADA RTU at each site. Once in the SCADA system, this data can be relayed to the office for water use accounting. The signal from the pressure transducer on the well outlet is used to regulate the operation of the VFD.

Figure 3. Two district supply wells directly coupled to three metered farm deliveries. The well at the right has VFD to regulate pressure. A farm booster pump is installed under shade at left.

A&B has also installed four Magna-Drive variable speed drives. Unlike the electronic VFD drives, the Magna-Drive uses a magnetic clutch assembly connected between the pump motor and the pump shaft to adjust pump speed. The clutch consists of two large permanent magnets that are separated by an adjustable air gap. The drive unit's electronic controller monitors pump outlet pressure and adjusts the width of this gap using a small electric actuator. The gap is increased to slow the pump speed and decreased to increase the pump speed.

One of the Magna-Drives is installed on a 300 hp horizontal electric motor and transmits power to the well shaft through a 90-degree gearbox. The other three Magna-Drive units fit between the well shaft and a vertical electric motor and include the necessary thrust bearings for this type of installation. All 4 Magna-Drive sites are monitored by the District's SCADA system.

Both types of variable speed drives have been successful in reducing both the amount of water withdrawn from the aquifer as well as reducing power consumption. Each type of drive also has its own benefits and detriments.

The VFD's are relatively large and must be installed in small weatherproof structures. The electronic components used to adjust the frequency of the alternating current of the power supply generates a good deal of heat inside the instrument building, which must be air conditioned. VFD's are designed to work with specific voltages. The District was not able to obtain VFD's for the 2300-

volt equipment originally installed on project wells and had to install 480-volt motors and transformers at all of the VFD sites. The VFD's have helped reduce energy use and have been quite reliable. They have also been relatively easy to integrate into the district's SCADA system.

The Magna-Drive units were able to work with existing voltages, but did require additional modifications at the well sites. When the first Magna-Drive was installed, only horizontal units were available. The district had to replace the existing vertical motor with a horizontal motor and a 90-degree, oil-filled gearbox. Both Magna-Drive units have high-speed cooling fans which may not be suitable for all locations due to the fan noise. Magna-Drive units cost more than VFD units for similarly sized pumps and, with more mechanical components, have required more maintenance.

Automatic Regulating Valves

At most farm deliveries where district wells are directly connected to farm pumps, flow meters with electronic outputs are connected to the well's SCADA system to monitor flows. Automatic valves are used to control farm delivery pressures. Because A&B used federally subsidized electric power for its supply wells, farm delivery pressures must be minimal.

Two types of regulating valves are used in these installations. At one site, motorized butterfly valves with valve position sensors are adjusted by the RTU at the well to maintain proper pressures at the well outlet. At 24 other sites, Nelson diaphragm valves are installed between the well head and the farm pump to automatically regulate to the preset pressures.

On-farm Improvements

Between 1980 and 2005, the B Unit has gone from 20% to over 60% sprinkler irrigation. The A&B Irrigation District has worked closely with the local Minidoka Soil and Water Conservation District and the Natural Resources Conservation Service to assist district farmers with the conversion of their farm irrigation system from gravity application to sprinklers. Also, the Conservation District has worked with the EQIP and other federal programs to assist landowners with installation of approximately 30 new sprinkler systems since 2002.

In many cases, district distribution laterals must be relocated to "square-up" fields to install new center pivot or side-move sprinkler systems. A&B has assisted in these instances by donating district equipment and manpower to help install landowner-purchased pipelines to relocate or bury district laterals.

SUMMARY

The A&B Irrigation District and its irrigators have utilized a wide range of technologies and management improvements to help mitigate the impacts of declining water levels in the Eastern Snake Plain Aquifer in southern Idaho. Improved irrigation application methods, a district-wide SCADA network, variable speed well pump drives, and distribution system efficiency improvements have helped A&B to cope with reduced groundwater supplies and increased pumping costs.

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REFERENCES

Whitehead, R.L. 1994**.** GROUND WATER ATLAS of the UNITED STATES Idaho, Oregon, Washington - HA 730-H. U.S. Geological Survey Publication.

Idaho Department of Water Resources. 1998. Resource Inventory Upper Snake River Basin, December 1998.

AN ON-LINE ADVISORY PROGRAM FOR OPTIMUM IRRIGATION MANAGEMENT

Charles Hillyer[1]
Marshall English[1]
John Busch[2]
Carole Abourached[1]
Chadi Sayde[1]

ABSTRACT

Conventional irrigation practices are predicated on maximizing crop yield – a biological objective. As worldwide competition for water intensifies a fundamentally new paradigm for irrigation management is emerging predicated on maximizing net returns to water – an economic objective. Maximizing returns to water generally involves some degree of deficit irrigation, particularly when water supplies or system constraints limit the availability of water, but few farmers are well equipped to deal with the analytical challenges associated with managing water deficits. This paper presents a web based advisory service for irrigation management now in use in a pilot program in Oregon. While the system can be used for conventional irrigation scheduling it is designed explicitly to assist irrigation managers with planning and implementing optimum irrigation strategies when water supplies are limited or expensive. Though originally developed for use in Oregon, discussions with other states have been initiated to make the system available nationally. This paper provides an overview of the analytical framework and demonstrates primary features of the user interface.

INTRODUCTION

A web-based irrigation advisory program, funded by NRCS and managed by Oregon State University, has been developed to assist irrigators with maximizing net economic returns to water. Economic optimization will frequently involve some degree of deficit irrigation, and that presents challenging management problems, including: (i) irrigation efficiency cannot be determined *a priori*. Since efficiency is linked to irrigation intensity it must be derived from the management strategy chosen; (ii) where water supplies or system delivery capacities are limited irrigation of all fields must be scheduled conjunctively to allocate water most effectively; (iii) conjunctive irrigation scheduling of multiple fields requires that farm water delivery constraints be taken into account; and (iv) since deficit

[1] Biological and Ecological Engineering Dept., Oregon State Univ., Corvallis OR 97331; hillyer@engr.orst.edu, englishm@engr.orst.edu, abouracc@onid.orst.edu, saydec@onid.orst.edu
[2] USDA-Natural Resource Conservation Service, Baker City, OR; John.Busch@or.usda.gov

irrigation implies yield loss it is necessary to estimate the yield impacts of management strategies.

Few commercial farms are equipped to deal with these questions. The program discussed in this paper will assist farmers in meeting these management challenges, and as such it represents a significant departure from earlier scheduling programs. The general plan for the system was developed in 2004 and refined during user-group meetings in seven locations around Oregon. The design philosophy was to account for specific farm circumstances and bring the irrigation manager's experience and preferences into the analysis. Since different managers have different objectives and tolerance for risk and face different local circumstances their preferred irrigation strategies will differ. The procedure for determining optimal allocation of limited water will therefore be based on an iterative, directed search that utilizes several program features designed to meet the analytical challenges of optimum irrigation management:

- The program provides for simultaneous scheduling of multiple fields in order to analyze strategies for apportioning limited water;
- It explicitly accounts for delivery system capacities, water supply constraints and intervals when irrigation is precluded by other farm operations;
- It provides full-season forecasting of irrigation requirements based on historical weather (high, low and average water demand years), enabling the manager to develop seasonal water use plans and/or anticipate water shortages as the season progresses;
- It allows the user to consider alternative, unconventional scheduling strategies such as reduced irrigation adequacy, partial season irrigation and user-stipulated irrigation dates;
- It analyzes the application efficiency that will derive from stipulated management strategy by modeling determinants of water losses (spatial variability of soils, irrigation uniformity, irrigation timing and adequacy, surface runoff and redistribution).

The system will eventually include three primary elements, two of which are now operational. The first is a general model of irrigation efficiency (IEM) that analyzes the disposition of applied water as spray losses, surface retention, runoff and redistribution, infiltration, percolation, evaporation and transpiration. The second is a robust, user-friendly, web-based 'expert' user interface (OISO). The interface obtains Penman estimates of reference ET from a regional weather station network, uses IEM to analyze irrigation requirements, then communicates advisory information to client farms and obtains operational data from them. These first two elements have been in beta testing with cooperating farms and are to be installed on the NRCS web farm in Fort Collins this fall. The third primary element, which is still in development will provide estimates of yields reductions when irrigation intensity is reduced.

The irrigation efficiency model (IEM)

The Irrigation Efficiency Model is designed to model the relationship between irrigation intensity, water losses and crop water use. IEM was originally developed by Oregon State University and the New Zealand Ministry of Agriculture and Fisheries (English 1992), then further developed and refined with funding from a USDA National Research Initiative grant (Isbell 2005). The model is implemented in C# and uses a variant of the MODCOM simulation framework (Hillyer 2003). The implementation is modular and was designed with the anticipation of future extensions and modifications.

IEM functions as a soil water balance model, tracking irrigation and precipitation inputs, estimating potential crop ET, adjusting the potential ET to account for low soil moisture or wet surface conditions, and partitioning ET into its component parts of evaporation and transpiration using the algorithms outlined in FAO 56 (Allen 1998). When soil moisture reaches a user specified level of allowable depletion the model calculates the gross irrigation requirement, expressed as the duration of irrigation required to bring soil moisture up to a user specified refill level. Calculations of gross irrigation requirements are based on net irrigation requirement and an *assumed* application efficiency provided by the user. Subsequently, when an irrigation takes place, IEM simulates *actual* application efficiencies by modeling the principal determinants of irrigation losses, including spatial variability of soil characteristics, irrigation timing and adequacy, patterns of applied water, wind effects on spray losses, wind distortions of sprinkler patterns, variability of surface infiltration rates, and surface water accumulations and redistribution. By simulating these factors the model analyzes the disposition of applied water in terms of evaporative losses, percolation, and runoff.

Simulation of the variability of soil moisture in a heterogeneous field with non-uniform water applications is a particularly important aspect of IEM. Such spatial variability has important implications for irrigation scheduling, and can be an important factor in yield modeling. These points are illustrated by Figures 1, 2, 3 and 4. Figure 1 shows a histogram of measured 'field capacities' in a small area (one acre) of a silt loam soil that illustrates the innate variability of soil water holding characteristics. That variability has two important implications. First, since net irrigation requirements are commonly based in part on field capacity, the variability indicated by Figure 1 implies that net irrigation requirements depend upon which part of a heterogeneous field is considered the 'control' sector for scheduling purposes. Secondly, since it is common practice to rely on soil moisture measurements to determine 'true' soil moisture, the variability shown in Figure 1 implies that such soil moisture measurements must be treated as highly uncertain. These two conclusions will not be news to experienced irrigation managers, but they illustrate the rationale for simulating spatial variability.

The variability in Figure 1 is less useful as an indication of crop water availability. Given the integrating effect of root distributions and lateral flow of soil water the true variability of crop available water is likely to be less than this histogram would suggest. On the other hand larger scale variations commonly seen in field soils may cause much greater variations than suggested by Figure 1. Figure 2, taken from the NRCS soil survey for Oregon, shows a field comprised of two distinctly different soils, one with an available water capacity of 2.3 in/ft to a depth of more than 5.0 feet, the other an AWC of 1.7 in/ft to 2.0 ft. These imply much greater field-wide variation than that suggested by Figure 1.

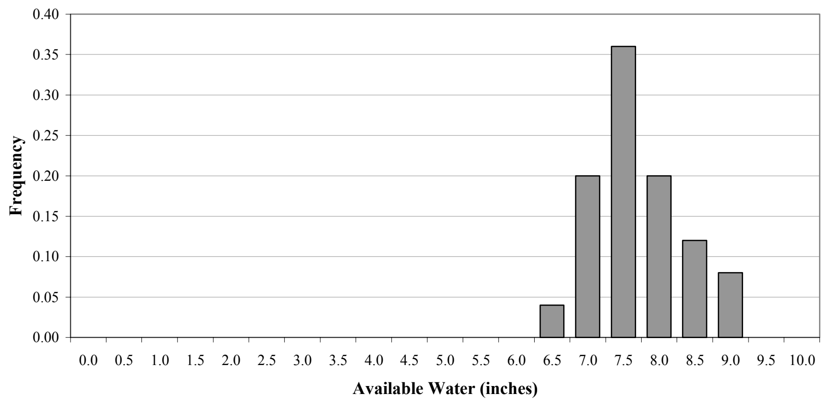


Figure 1. Variability of field capacity in a homogeneous silt loam soil

Variations in crop available water imply corresponding variations in crop yield. Figure 3 shows an IEM simulation of the spatial variability of T in a relatively homogeneous field irrigated at 90% of cumulative ET. Histograms of transpiration in Figure 4 show the changing spatial pattern of T in a relatively uniform field irrigated at intensities of 60%, 80% and 100% of potential ET (Isbell 2005). The variance of T at 100% irrigation is small, but as irrigation is reduced the variance of T increases and the shape of the probability density function changes. If crop yields are assumed to be more or less linearly related to ET or T these spatial patterns of ET imply corresponding patterns of crop yield. The importance of such patterns, if any, is being analyzed at this time.

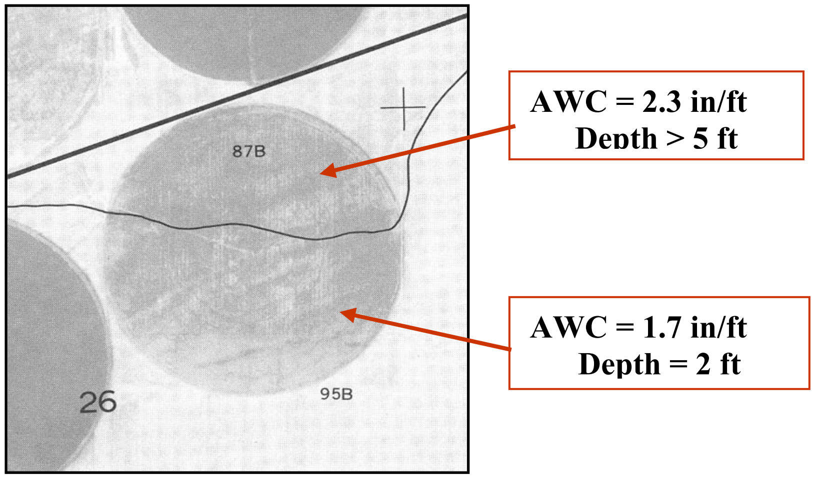


Figure 2. Two soil types in a single field

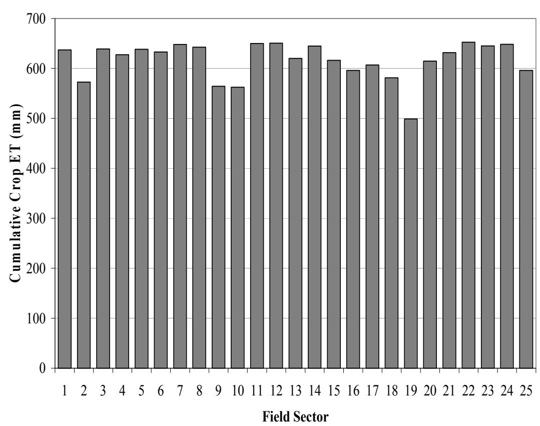


Figure 3. Distribution of Cumulative Crop ET

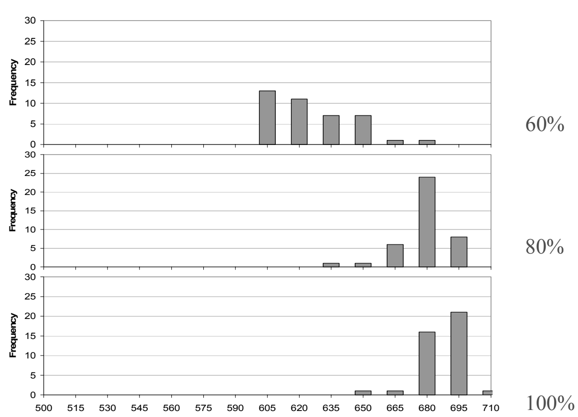


Figure 4. Simulated Distributions of Crop ET

Simulating the variability of soil water and crop available water provides a mechanism for explicitly accounting for these issues when formulating optimum irrigation strategies. That begs the question of how to determine the appropriate scale of variability for simulation purposes. At present that is left to the user's judgment, though default values are provided by the system.

Web based interface (OISO)

OISO analyzes operations for a single water source (called a water management unit, or WMU) and multiple fields that share that water source. The program is initialized by first entering the WMU command area, delivery rates and volumes. The following inputs then define the fields and irrigation systems that share that water supply:

(i) descriptions of each field include area, crop type and development dates, soil depths, infiltration rates, water holding characteristics and antecedent moisture;
(ii) irrigation systems are described by system type (e.g. pivots), application rates, nominal rotation times, estimated uniformity coefficients and sprinkler head configurations.
(iii) irrigation management strategies are described in terms of MAD, refill level, application efficiency to be assumed for calculating gross irrigation requirements, and the field sector (defined by the total water holding capacity) to be used for scheduling purposes.

As noted earlier, a weather station network provides daily Penman reference ET[3]. OISO downloads recent weather data, then calls IEM to calculate soil moisture (including spatial variations in moisture) on a daily basis, determine when irrigations are required and calculate the depths of water that need to be applied. When an irrigation event occurs IEM analyzes the disposition of the applied water as previously outlined. Outputs to the user indicate soil moisture status on a daily basis and recommendations for timing and duration of upcoming irrigations. The program forecasts crop water demand from the current date to the projected season end date. A typical graphical output for a single field is shown in Figure 5, with irrigation events (red) and precipitation (green) shown along the horizontal axis.

[3] At present the system is linked to the USBR Agrimet network.

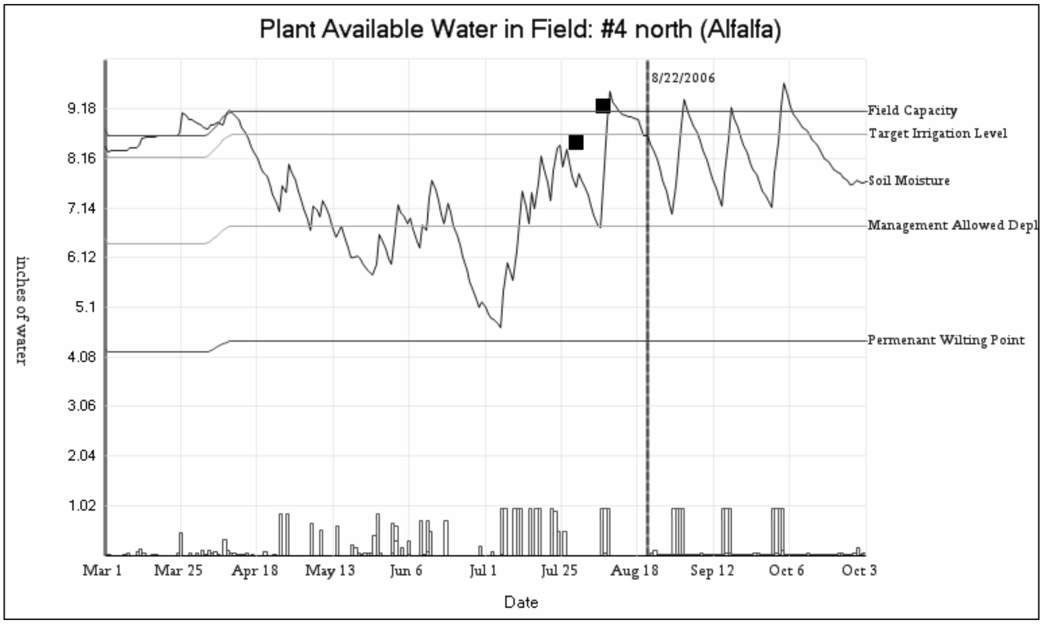
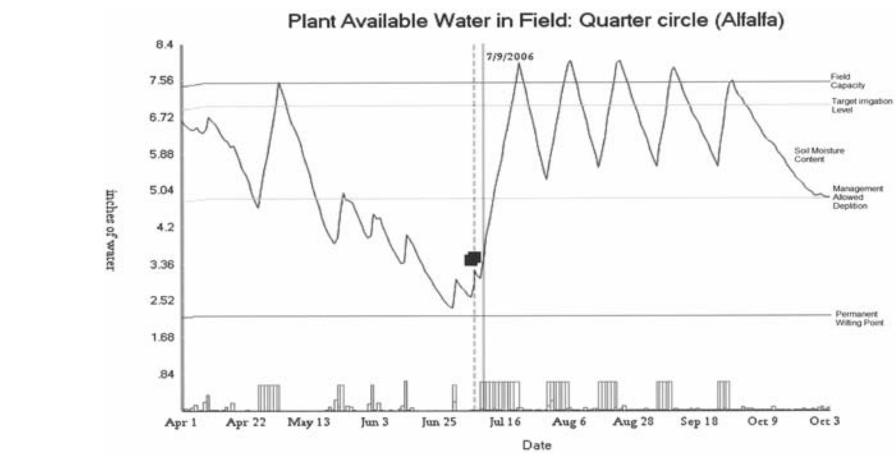


Figure 5. Typical graphical output

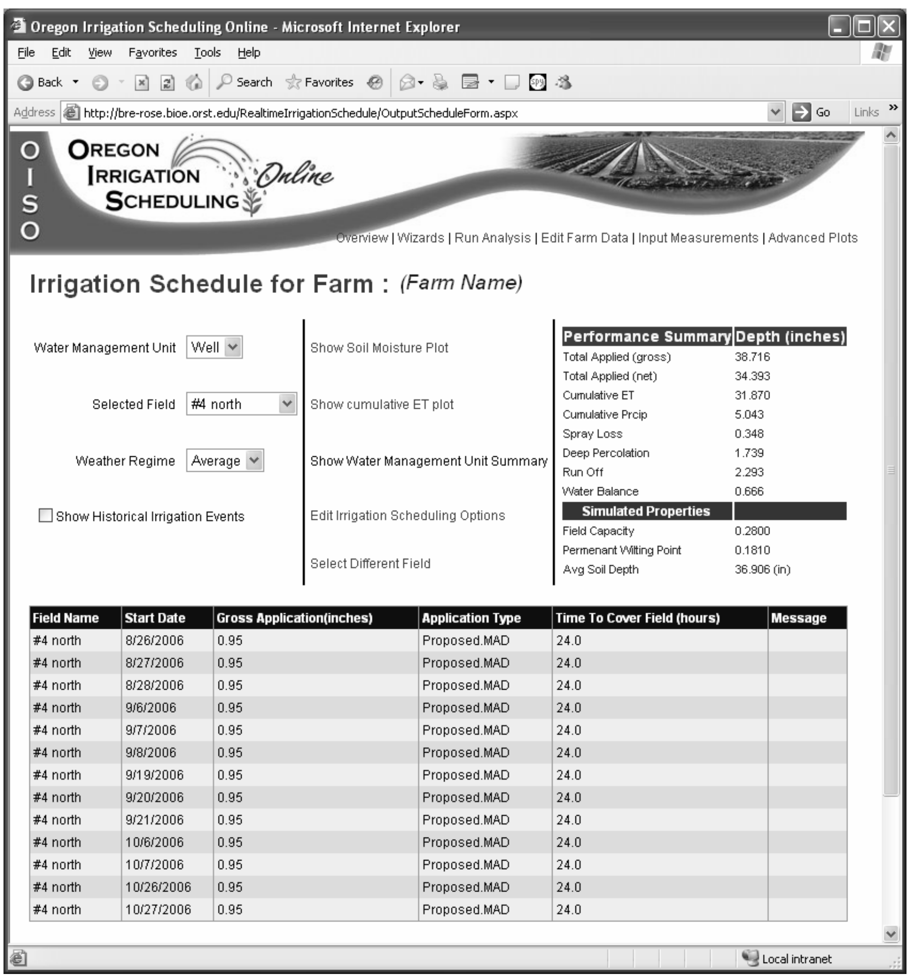


Field Name	Aug/ 20	Aug/ 21	Aug/ 22	Aug/ 23	Aug/ 24	Aug/ 25	Aug/ 26	Aug/ 27	Aug/ 28	Aug/ 29	Aug/ 30	Aug/ 31	Sep/ 1	Sep/ 2
#4 north					900	900	900	900						
#4 Southeast														
#4 southwest	900	900	900	900								900	900	900
Total	900	900	900	900	900	900	900	900				900	900	900

Dear Mr. …..
The above OISO analysis is a summary for July 8th. The last irrigation date entered was June 28th. The last cutting of alfalfa was June 10th and the next assumed alfalfa cutting date is July 15th. If there have been more recent irrigations, or soil moisture measurements please let us know by *reply email* or call 541-602 6845. For more complete details you can go directly to the web site:
http://bre-rose.bioe.orst.edu/Realtimeirrigationschedule/index.htm

Figure 6. Sample daily output to client

The graph shows recent history of soil water up to the current date (left of the vertical line), then a forecast of required irrigation dates and soil moisture to the end of the season. The black squares represent measurements of soil moisture. A two week calendar of upcoming irrigation events is also presented. The system provides a 'push-pull' communication link in which daily email messages are sent to individual clients presenting the current status of the individual fields and inquiring about the previous day's farm operations. By simply picking the *reply email* hot button the client can easily send back current operational information such as recent irrigation events, soil moisture measurements or alfalfa cuttings. Clients wishing to see more complete analyses can access their individual web pages by picking the URL. Figure 6 is a prototype message currently being generated manually by project personnel. Ultimately such messages will be generated automatically. The website will also generate a calendar of irrigation dates and rates (Table 1), detailed tables of irrigation dates and amounts (Figure 7), detailed plots of soil moisture, evapotranspiration, and cumulative application for multiple weather regimes.



Oregon Irrigation Scheduling Online - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://bre-rose.bioe.orst.edu/RealtimeIrrigationSchedule/OutputScheduleForm.aspx

OISO Oregon Irrigation Scheduling Online

Overview | Wizards | Run Analysis | Edit Farm Data | Input Measurements | Advanced Plots

Irrigation Schedule for Farm : *(Farm Name)*

Water Management Unit: Well
Selected Field: #4 north
Weather Regime: Average
Show Historical Irrigation Events

Show Soil Moisture Plot
Show cumulative ET plot
Show Water Management Unit Summary
Edit Irrigation Scheduling Options
Select Different Field

Performance Summary	Depth (inches)
Total Applied (gross)	38.716
Total Applied (net)	34.393
Cumulative ET	31.870
Cumulative Prcip	5.043
Spray Loss	0.348
Deep Percolation	1.739
Run Off	2.293
Water Balance	0.666
Simulated Properties	
Field Capacity	0.2800
Permenant Wilting Point	0.1810
Avg Soil Depth	36.906 (in)

Field Name	Start Date	Gross Application(inches)	Application Type	Time To Cover Field (hours)	Message
#4 north	8/26/2006	0.95	Proposed.MAD	24.0	
#4 north	8/27/2006	0.95	Proposed.MAD	24.0	
#4 north	8/28/2006	0.95	Proposed.MAD	24.0	
#4 north	9/6/2006	0.95	Proposed.MAD	24.0	
#4 north	9/7/2006	0.95	Proposed.MAD	24.0	
#4 north	9/8/2006	0.95	Proposed.MAD	24.0	
#4 north	9/19/2006	0.95	Proposed.MAD	24.0	
#4 north	9/20/2006	0.95	Proposed.MAD	24.0	
#4 north	9/21/2006	0.95	Proposed.MAD	24.0	
#4 north	10/6/2006	0.95	Proposed.MAD	24.0	
#4 north	10/7/2006	0.95	Proposed.MAD	24.0	
#4 north	10/26/2006	0.95	Proposed.MAD	24.0	
#4 north	10/27/2006	0.95	Proposed.MAD	24.0	

Local intranet

Figure 7. Sample web site output screen

The full potential of this system becomes clearer when planning water use for multiple fields with limited water. That problem, for which this system was originally designed, is illustrated by
Figure 8 which shows monthly crop water demand for each of four crops on six fields during the 2002 crop year and aggregate demand for all fields on a cooperating farm in eastern Oregon. The horizontal line indicates the farm water supply. At peak of season the water demand for full irrigation is about 80% greater than the supply. Clearly it is not possible to fully irrigate all six fields, but strategic timing and deficit irrigation strategies have enabled this farm to manage these fields profitably in water short years. The present program is designed to deal with the unconventional strategies that farms such as this have developed use over the years.

Since different managers have different objectives and tolerance for risk and face different local circumstances their irrigation strategies will differ. Consequently, determining the allocation of a given water supply among several fields is based on an iterative, directed search that accounts for specific farm circumstances and brings the manager's local experience and preferences into the analysis.

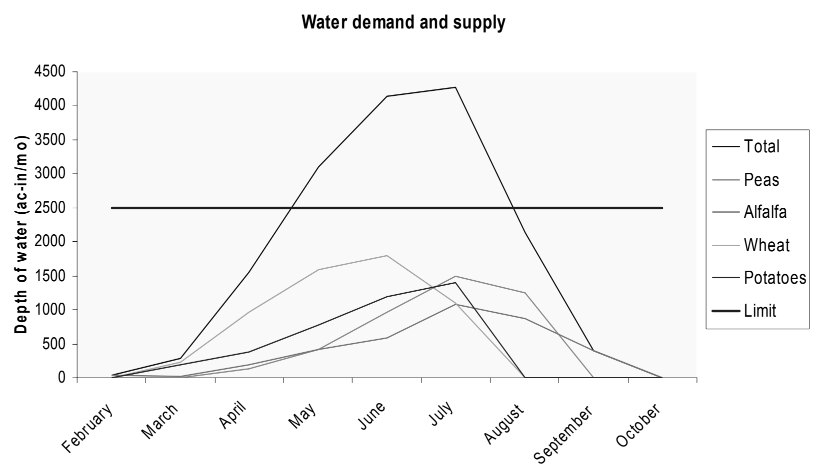


Figure 8. Nominal Crop Water Demand for four crops on Seven Fields

The procedure consists of these steps:

(i) propose a water management plan, consisting of a cropping pattern, irrigation system configuration and irrigation management strategies for each field
(ii) estimate daily water demand and resulting crop yields for each field for weather years of low, average and high water demand.
(iii) compare total demand with available water supply and delivery system capacity
(iv) if the water demand exceeds available supply or system capacity, adjust the cropping pattern and/or irrigation plan and repeat the analysis until a

feasible strategy is found such that the total demand is in-line with available water.

An example seasonal water use plan form the same cooperating farm[4] is shown in Figure 9 showing color coded graphs of projected irrigation dates and delivery rates (gallons per minute) for irrigation of five crops on seven fields of various sizes with a variety of irrigation systems. The resulting aggregate farm water demand, summed for all fields, is also shown (black line). Total farm water delivery capacity, about 2400 gpm, is shown as a horizontal line. As in the earlier example, the water demand would exceed supply for much of the season, particularly in May and June, so the initial water use plan shown here is not feasible. Several changes might then be proposed to deal with this water shortage; (i) a small field of alfalfa in its last year of production could be fallowed, (ii) a second field of alfalfa could be deficit irrigated, (iii) alfalfa cutting dates could be shifted slightly, and (iv) a circle of winter wheat could be deficit irrigated.

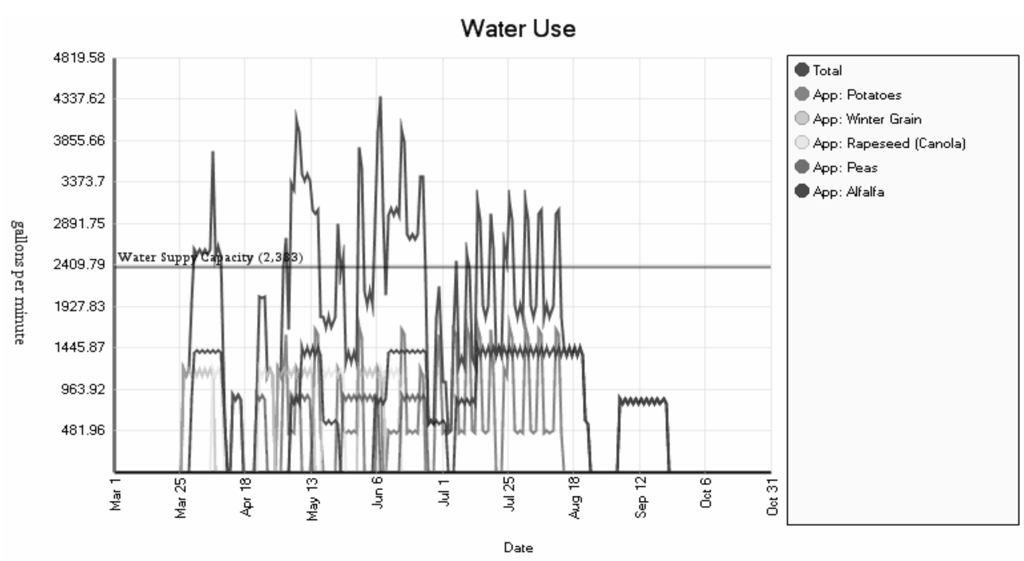


Figure 9. Seasonal Water Demand on a Cooperating Eastern Oregon Farm

[4] This plan is for a different crop mix than was in place in 2002.

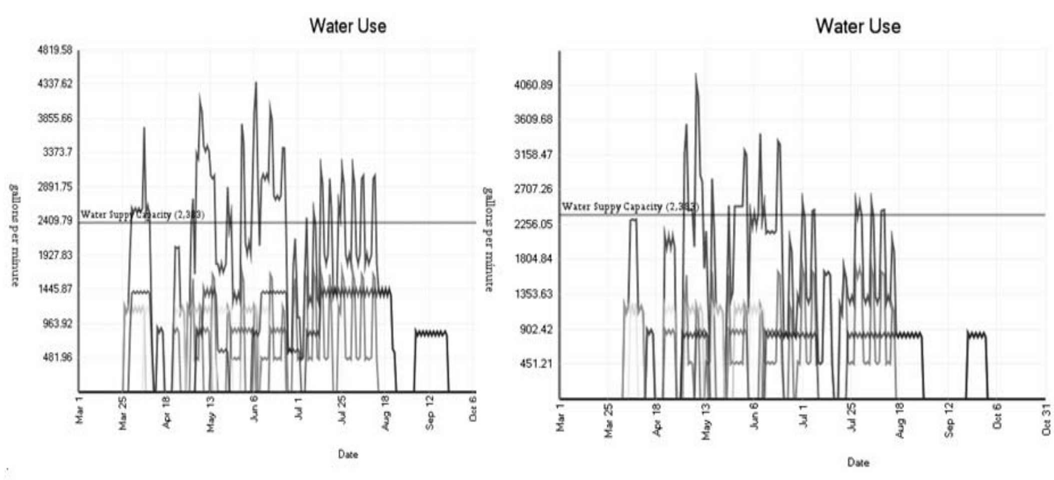


Figure 10. Original & Revised Water Demand Plots

Figure 10 compares the first water demand graph (left) with the resulting revised graph (right). The proposed changes would substantially reduce overall demand, and shorten most periods of excess demand which would make the water shortages more manageable. The next step would be to further refine the irrigation schedules on a day-by-day basis, shifting irrigations from specific high demand days to days when capacity is under-utilized. Table 1. shows the two-week calendar of irrigation dates and rates (gpm) for the period beginning June 4 for all seven fields, with daily totals along the bottom line. On days when demand exceeds capacity the aggregate is shown in red.

During the coming winter the program will be modified to allow direct editing of the scheduling calendar, deleting or adding entries for specific dates, or clicking and dragging strings of entries, until the total demand for each date is brought in line with supply. The concept is illustrated in Table 2, which shows two minor changes in the recommended schedule. By starting canola irrigation one day earlier and eliminating the last day of a scheduled irrigation of wheat the two days of excess demand could be avoided.

Table 1. Calendar of Irrigation Dates & Rates

	Jun/4	Jun/5	Jun/6	Jun/7	Jun/8	Jun/9	Jun/10	Jun/11	Jun/12	Jun/13	Jun/14	Jun/15	Jun/16
43 potatoes									480	480	480	480	480
44 alfalfa										850	850	850	850
45 peas									900	900	900	900	900
46 alfalfa													
47 wheat	1200	1200	1200	1200	1200	1200	1200						
48A potatoes							1200	1200					
48B canola		1200	1200	1200	1200	1200	1200	1200	1200				
Total	1200	2400	2400	2400	2400	2400	3600	2400	2580	2230	2230	2230	2230

Table 2. Editing Irrigation Dates

	Jun/4	Jun/5	Jun/6	Jun/7	Jun/8	Jun/9	Jun/10	Jun/11	Jun/12	Jun/13	Jun/14	Jun/15	Jun/16
43 potatoes									480	480	480	480	480
44 alfalfa										850	850	850	850
45 peas									900	900	900	900	900
46 alfalfa													
47 wheat	1200	1200	1200	1200	1200	1200	1200						
48A potatoes							1200	1200					
48B canola		1200	1200	1200	1200	1200	1200	1200	1200				
Total	1200	2400	2400	2400	2400	2400	3600	2400	2580	2230	2230	2230	2230

Additional plans for modifying or expanding the system this year include linking the farm setup wizards to NRCS on-line, GIS-based soils data and expanding the system options to include micro-irrigation and surface irrigation methods.

REFERENCES

English, M.J., A.R. Taylor and S. Abdelli.1992; A Sprinkler Efficiency Model. *ICID Bulletin*, Vol.41: 2

FAO 56. Allen R.G., Pereira L.S., Raes D. and Smith M., 1998, Crop evapotranspiration: Guidelines for computing crop water requirements. Food and Agriculture Organization of the United Nations irrigation and drainage paper 56.

Hillyer, C.H., Bolte, J., van Evert, F., Lamaker, A., 2003, The ModCom modular simulation system. *European Journal of Agronomy* 18: pp. 333 – 343.

Isbell, B. M. 2005. "An Irrigation Efficiency Model for Optimum Irrigation Management". MS Thesis, Bioengineering Department, Oregon State University, June.

INSTITUTIONAL REFORMS IN THE WATER SECTOR OF PAKISTAN

Altaf A. Abro[1]
Ralph K. Davis[2]

ABSTRACT

Water is becoming increasingly scarce all over the world. Indicators of water availability show that per capita supplies will continue to decline in the years ahead. The situation for Pakistan is even more critical as irrigated agriculture plays a very vital role in Pakistan's economy; the sector accounts for 24.5% of country's Gross Domestic Product (GDP), employs 55% of the labor force and accounts for 80% of the total export earnings of the country. Unlike population, water availability per capita is persistently decreasing in Pakistan, which would presumably affect food sufficiency for the projected population of 250 million in year 2025. Scarcity of irrigation water is a main concern for policy makers and planners in Pakistan. Prospects for increasing water supplies through construction of new storage reservoirs are not encouraging, as development of water resources has approached its limit. Construction of new reservoirs may not be economically, nor environmentally realistic for Pakistan. Therefore, Pakistan needs to explore alternative solutions to meet the increasing demand for water.

This paper is based on the proposition that water scarcity results from ineffective and inefficient water resources management in Pakistan, which is partially due to the inadequacies of regulatory and planning structure, and slow implementation response to the proposed changes in institutional structure. Water institutions and water management are undergoing enormous changes world wide. It is assumed that the government of Pakistan will not be able to manage water resources efficiently without removing impediments to planning and management as part of this reform process. This paper describes the reform process, and the ensuing institutional change sought by the reforms in the irrigation sector of Pakistan.

INTRODUCTION

Water is essential for sustaining the quality of life on Earth. This finite commodity has a direct bearing on almost all sectors of the economy. In Pakistan its importance is more than ordinary due to the significance of the agrarian nature of the economy. The share of the agricultural sector in the GDP of Pakistan is 24.5 % (Pakistan Agricultural Statistics, 2003). Agriculture is the major water user, consuming about 82% for irrigation (Pakistan Agricultural Statistics, 2003);

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[1] Public Policy Ph.D. Candidate, University of Arkansas, Fayetteville, AR-72701, USA. Email:altafabro@hotmail.com

[2] Associate Professor and Director of Arkansas Water Resources Center (AWRC), Department of Geosciences, University of Arkansas, Fayetteville, AR-72701, USA. Email:ralphd@uark.edu

therefore sustainability of agriculture depends on the timely and adequate availability of water. The increasing pressure of population and industrialization has already placed greater demands on water, with an ever-increasing number and intensity of local and regional conflicts over its availability and use.

Historically, the high aridity index of the country has also added further to the significance of water in developmental activities in Pakistan. Though, once a water-surplus country with huge water-resources of the Indus River System, Pakistan is now a water-deficit country. At present, the annual per capita water-availability in Pakistan is about 1100 cubic meter (m^3); below 1,000 m^3 countries begin experiencing chronic water stress (Population Action International, 1993). The situation in Pakistan indicates that the country is nearing conditions of absolute water scarcity (World Bank, 2005). Meanwhile, the gap between demand and supply is increasing, requiring the government of Pakistan to explore alternative water resources. One alternative to meet this demand is through more efficient delivery, which might result from timely institutional reforms in the water planning and management sector.

Water institutions and water management are undergoing remarkable changes world wide. The era of water abundance is long over, but unfortunately policy makers are still stuck with the supply oriented approach of 1940s to 80s, when engineering solutions were considered the only panacea to solving global problems of water scarcity. Perception of those revolved around expanding supply through enlarging physical and technical infrastructure mainly financed from public sources. The Dublin Principles (1992) and subsequent international events paved the way for water sector reforms and pointed out institutional weaknesses that were causing institutional inefficiencies in the water management (Neubert, et. al., 2002).

This paper is based on the proposition that water scarcity results from ineffective water resources planning and management in Pakistan, which is partially due to the inadequacies of regulatory and planning structure, and slow implementation response to the proposed changes in the institutional structure. The government of Pakistan will not be able to effectively manage water resources without removing the impediments to planning and management as part of an overall reform process. This is needed to be able to feed its projected population of 250 million in year 2025. The paper aims to explore the causes of institutional deterioration in water sector of Pakistan and seeks to answer the question; why there has been slow implementation response to the proposed changes in the institutional structure?

WATER RESOURCES AND THE ISSUE OF WATER SCARCITY

Pakistan contained six rivers within its geographic boundaries in 1947. Under the World Bank brokered Indus Basin Treaty between India and Pakistan in 1960 Pakistan gave up three eastern rivers; Ravi, Beas and Sutlej. Pakistan's availability of water was then limited to three western rivers, namely Indus, Jhelum and Chenab. The World Bank provided funds for the construction of a number of link canals, barrages and dams on the Indus and its two tributaries, Jhelum and Chenab, transferring at least 20 MAF of water for the irrigation of areas that were cut off from irrigation-systems of eastern rivers (Kahlown and Mujeed, 2001).

The Indus River alone provides 65% of total river flows to Pakistan, while the share of Jhelum and Chenab is 17 and 19 %, respectively. Table 1 shows the maximum and minimum inflow of western rivers for summer and winter seasons, that is highly erratic. Besides, those three major rivers Pakistan has numerous small rivers and streams, which are only seasonal, with flow depending largely on timing and distribution of rainfall. These smaller streams practically run dry during the winter months. Table 2 presents the water requirement and availability situation for year 2000 and projected figures for year 2025. The important thing to notice here is that water availability will remain the same (if no new water resources were developed), however the shortfall will increase from 12.61 MAF in year 2000 to 30.26 MAF in year 2025.

Table 1. Inflows in Western Rivers (in MAF)

	Kharif (summer)	**Rabi (winter)**	**Total**
Maximum (Year)	154.7 (1959-60)	35.1 (1990-91)	186.8 (1959-60)
Minimum (Year)	71.5 (1999-2000)	15.7 (1971-72)	97.7 (1971-72)
Mean (77 Years)	115.9	22.8	138.7

Source: Water and Power Development Authority (WAPDA), and Indus River System Authority (IRSA) Reports, and Kahlown and Mujeed, 2001.

Table. 2: Water Requirements and Availability

Requirement / Availability	**Year**	
	2000 (MAF)	2025 (MAF)
Surface Water requirements	116.42	134.07
Average water availability without additional storages	103.81	103.81
Shortfall	12.61	30.26
Percentages (%)	10.83%	22.56%

Source: WAPDA, 2003 ‘Pakistan’s Vision of Water Resources Management.’

Rainfall

June to September are the peak precipitation months when about 70 percent of the annual rainfall occurs. The mean annual rainfall distribution in Pakistan has a broad regional variation. It ranges between 125 mm in Balochistan to 750 mm in the Northwest (Kahlown and Mujeed, 2001). Rainfall is neither sufficient nor regular. In the Sindh Plains, high-intensity rainfall occurs during July and August, and its intensity continues to decrease from coastal areas towards central parts of Sindh.

Southern Punjab and northern Sindh are the areas of very low annual rainfall-less than 152 mm, and the winter rains are generally widespread. Northern and northwestern area of North West Frontier Province (NWFP) and the northern areas of Balochistan receive comparatively higher rainfall during winter. The magnitude of the annual rainfall over nearly 21 million hectares (Mha) of the Indus Plains averages about 26 MAF. The present contribution of rain to crops in the irrigated areas is estimated at about 6 MAF.

Groundwater Resources

Alluvial deposits of the Indus Plain that store most of the groundwater resources of Pakistan stretching from the Himalayas to the Arabian Sea (Kahlown and Mujeed, 2001). The Plain which is about 1,600 km long, and covers an area of 21 Mha is fast becoming a supplemental source of water for irrigation in Pakistan. The aquifer has the potential for about 50 MAF. According to some conservative estimates, about 562,000 private tube-wells and 10,000 public tube-wells in the region are currently exploiting the aquifer to an extent of about 38 MAF (Kahlown and Mujeed, 2001).

There are about 837,000 ha in production in Balochistan province of Pakistan. About 96% of these 837,000 ha are irrigated, while the remainder is dryland agriculture. The province is badly short of irrigation water, only 0.8 M.Ha of irrigation supply is deverted in the entire province (ICID, 2005). The main sources of irrigation are government and private canals, wells and tubewells, karezes and springs that irrigate orchards and other cash crops. Rivers and natural streams run temporarily and remain dry for most part of the year. Consequently groundwater is being overexploited beyond its recharge potential especially in Pishin-Lora and Nari basins (ICID, 2005).

INSTITUTIONAL SETTING

According to North (1990) institutions are the rules of the game in a society or, more formally, are humanly devised constraints that shape human interaction. As a result of this they structure incentives in human exchange, whether political, social, or economical. Saleth and Dinar (1995) note “water institutions entail rules that describe action situations, delineate action sets, provide incentives and determine outcomes both in individual and collective decisions related to water development, allocation, use and management.”

Pakistan is a federal system country and water is mainly the federal government’s business. Provinces are mainly the managers of the water sector, with constitutional power to modify irrigation management. There are several laws and regulations[3] for water management and administration that are administered by the federal and the provincial institutions involved in water management.

In 1958 the Water and Power Development Authority was established at the Federal level through the WAPDA[4] Act (PWSS, 2002). Since then its mandate has been to undertake construction of large irrigation, drainage and hydropower projects. WAPDA is also responsible for generation, transmission and distribution of power in the country, except Karachi[5].

In 1982 Water User Ordinances were promulgated to form the Water User Associations (WUAs) to encourage farmer participation in water management at the watershed level. The underlying objective behind creation of WUAs was to collect contributions to civil works from water users. According to some government estimates WUAs in some areas contributed up to 55% of the cost of civil works for improvement of watercourses both in cash and in-kind services, and in the form of labor (PWSS, 2002). Since there was no vision to further involve WUAs in works greater than just contributions, almost all WUAs became dormant soon after the works were completed.

In order to introduce institutional reforms in the irrigation and drainage sector, the provinces enacted new Acts in 1997 (PWSS, 2002). These Acts provide the legal framework for establishment of Provincial Irrigation and Drainage Authorities (PIDAs), Area Water Boards and Farmer Organizations. The Pakistan Environmental Protection Ordinance was issued in 1983. It has been replaced with the Pakistan Environmental Protection Act, 1997. The Act is directed to provide a basic environmental policy and set up a management structure for pollution control.

The National Environmental Quality Standards (NEQS), enacted in 1993, delineates allowable limits for 32 pollutants in effluents and industrial discharges

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[3] The Canal and Drainage Act of 1873 is the main legislation that regulates the irrigation and drainage systems and has been adapted by various provinces. Other important piece of legislation is the Punjab Soil Reclamation (PSR) Act of 1952, which was later extended to cover the entire country. The PSR Act of 1952 governs the preparation of drainage and other related schemes.

[4] Water and Power Development Authority (WAPDA) is a federal institution under the ministry of water and power. Through recent decentralization reforms introduced by President Pervez Mushraf WAPDA has decentralized power distribution through creation of subsidiary companies, which undertake power distribution and collect the revenues.

[5] Karachi Electric Supply Company (KESC) is also a federal entity under the ministry of Water and Power that is responsible for operation and supply of electricity to Karachi.

along with other limits related to industrial and vehicular air emissions. Provincial EPAs / EPD are responsible for monitoring and implementing the NEQS (PWSS, 2002). Proper implementation and enforcement of the NEQS is poor due to lack of resources, equipment, and skilled staff, as well as insufficient training and monitoring programs. In 2000, the Initial Environmental Examination (IEE) and Environmental Impact Assessment (EIA) Regulations[6] were enacted which elaborate the modalities and implementation mechanism of EIAs and IEEs.

WATER MANAGEMENT STRATEGY IN TIMES OF SCARCITY

The need to use scarce water equitably not only among various societal sectors, but also among farmers has been a main concern since the early days of irrigation development in Pakistan. It is assumed the water situation will further worsen as Pakistan adds 4 million people a year. It is likely that one out of three people in Pakistan will face critical water shortages, "threatening their very survival".

In order to cope with water scarcity the government of Pakistan is considering several strategies. First and foremost the strategy has been to develop new water resources. The present government, is forcefully pursuing the building of reservoirs and dams without regard for provincial consent. Despite protest of smaller provinces, President Mushraf's recently inaugurated the Bhasha dam project[7]. If the project moves ahead successfully, it is expected to be completed in 2016. The second strategy, to use water more efficiently without adequate awareness and training has also been a failure. The third available water management strategy, to make better use of available water, is pursued to the extent that more water-efficient crops are considered. The major cause of failure for two latter strategies, however, has been absence of economic incentives or disincentives to promote more efficient water use and a different use of water.

At the tertiary (watercourse) level government encourages warabandi[8] system to manage the scarce water. Warabandi is an "integrated water management system"

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[6] EPA provides the policy and procedures for the filing, review and approval of environmental assessments. It defines the jurisdiction of federal and provincial EPAs and P&Ds, and also provides schedules for proposals the require IEE or EIA.

[7] India has conveyed an official protest to Pakistan against the construction of Basha Dam on the Indus River in Pakistan's Northern Areas. Protest has been made on the grounds that 'the dam is being constructed in territory that is part of the State of Jammu and Kashmir, which is an integral part of India by virtue of its accession to it in 1947'. According to media reports the reservoir of the dam, will inundate large parts of land in the "northern part of the State of Jammu and Kashmir".

[8] Bandaragoda and Rehman (1995) define "Warabandi as a time-based rotational method, which is designed to achieve equitable distribution of water available for

that aims to achieve efficiency, and equity in water use (Malhotra, 1982). Water use efficiency is to be achieved through the imposition of water scarcity on each and every user, and equity in distribution through enforced equal share of scarce water per unit area among all users by self monitoring rotation system.

In the beginning the rigidity of the fixed schedule was designed to prevent the exploitation of water rights. However, since then much has changed i.e. cropping intensities, and cropping pattern. Consequently, the water allocation per unit of land has become inadequate. Generally, the warabandi schedules have not been able to provide sufficient irrigation per unit area for the average cropping intensity (Bhatti and Kijne 1990, Bandragoda, 1996). Bandragoda (1996) notes "due to the increasing demand for water, some users have started to develop following strategies to overcome supply inadequacy through flexibility in water turns":

- Rotations of turns - two or more farmers, rotate their water turns to improve equity, and concurrently the flexibility of using the sanctioned supplies. This way, each week, a farmer will share the effects of lapses of water that may apply to a number of individual water turns.
- Merger of turns - in this arrangement two or more farmers use water during a single water turn. However, this often happens only when farmers belong to the same family.
- Substitution of turns. This type of operation is prevalent in instances where a farmer has a small landholding with a short-duration water turn. This farmer gives up his turn in favor of nearby large landowner. After two or three turns, the large landowner gives sufficient water to irrigate the entire plot of the small landowner.
- Exchange of turns. Farmers have the practice of increasing the flexibility of water supply by lending and borrowing canal turns.
- Trading of turns. When farmers cannot meet their water requirements for any reason, they buy canal water turns.

DRIVING FORCES BEHIND IRRIGATION REFORMS

There are several endogenous and exogenous factors that can cause institutional change (Saleth and Dinar, 1995). High subsidies and thus the burden on national and provincial treasuries, poor performance of irrigated agriculture, and economic

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a watercourse. The rotation is by water turns fixed according to a predetermined schedule specifying the day, time, and duration of supply to each irrigator in proportion to the size of the irrigator's landholding. For each watercourse, there is a Warabandi list giving the names of actual water users taking water from the sanctioned farm outlets along the watercourse, and the corresponding time turns allocated to each water user."

losses due to resource depletion were some of the driving forces behind institutional change in the irrigation sector of Pakistan. Since inception, the development of water resources in Pakistan has been dominated by the state and Federal government, which often used infrastructure financing to stimulate economic development. It was a common perception that the state bureaucracies would best be able to administer water allocation, maintain the infrastructure and limit free-riding behavior (Neubert, et. al., 2002).

State control of this type is not very typical in Pakistan. However, the situation is more or less the same in many other developing countries[9] (Neubert, et. al., 2002). State controlled irrigation systems in Pakistan failed to validate the assumptions that the government can better manage the water resources. Gross misallocation of resources, poor performance in supplying water in terms of time and place, and abysmal condition of infrastructure has seriously challenged the government role in the irrigation sector.

The World Bank and ADB, as in many other countries, have played an important role in initiating institutional change in Pakistan. The World Bank document; Pakistan: Irrigation and Drainage: Issues and Options (1993) pointed to poor irrigation performance that together with the lack of an efficient drainage system would have caused widespread water logging and salinity on irrigated land, inefficient water delivery and use, inequitable water distribution, and overexploitation of good-quality groundwater. The World Bank called on the government of Pakistan to reduce its public expenditure in the irrigated agriculture sector, to reorient the functions and organizations of state agencies, and to enhance farmers' participation and strengthen the role of the private sector. It also advocated strengthening of federal water agencies and provincial water authorities.

The World Bank emphasized the implementation of pilot projects at the tertiary level that include lining of watercourses and remodeling of outlets. However, whether the World Bank induced initiative for public sector reforms will achieve the intended objectives largely depends on the agenda of state bureaucracies (Neubert et. al. 2002). Bureaucracy in the case of Pakistan has been very critical, and has affected the design and implementation of reforms as observed in many other social sector programs; i.e. Ayub khan's Basic Democracy program, Mohammad Khan Junijo's Nai Roshni Schools and Benazir Bhutto's Peoples Program.

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[9] The large-scale irrigation system in Turkey for example is operated and maintained (O&M) by financially dependent state agencies that receive O&M budgets from national and provincial treasuries (Neubert, et. al., 2002).

PAKISTAN'S EXPERIMENT WITH WATER SECTOR REFORMS

The disappointing results of the International Water and Sanitation Decade (1981-1990) (Neubert et. al. 2002) compelled water experts to devise management plans that included institutional and socio-economic aspects of water management. Even more so, the Dublin Principles (1992) and subsequent international events pointed to institutional weaknesses as major causes of ineffective, inefficient, and unsustainable water services, and called for urgent attention to be paid to institutional reforms and capacity-building (Neubert et. al., 2002). Water institutions in order to be more effective need to evolve and change their focus, and methods of addressing challenges.

Policy-makers recognized the need for 'soft' solutions such as improved institutions, better management, and use of incentives to avert the water crisis. While the relationship between state agency and farmers was still asymmetrical, with the state controlling the technical expertise and subsidizing maintenance, a second approach was developed in Mexico at the beginning of the 1990s. Since then, governments in many developing countries have transferred the management of irrigation systems to user organizations, largely driven by their inability to raise sufficient revenues.

Contemplation and discourse on water sector reforms became serious and intense during the early 1990s. However, it is worth mentioning that the poor performance of SCARP[10] tube wells had already triggered the reforms in the water sector long before 1990. SCARP tube wells had been highly successful at lowering the water table and reducing soil salinity. However, operation and maintenance costs of the wells were enormous. The government did not recover these expenditures from the farmers. With the passage of time, tube wells began to deteriorate and service grew less reliable (World Bank, 2001). The transition pilot project was designed to resolve these problems by eliminating public tube wells in areas with plentiful fresh groundwater and enabling farmers to construct their own tube wells.

SCARP transition projects (1987) encouraged farmer participation in good-quality groundwater areas by transferring them to tube well owners (Vander and Edward, 1998). A second institutional shift came with the On-Farm Water Management Projects that addressed the significant water losses, up to 40 %, at the watercourse level. These projects were implemented by the newly established On-Farm Water Management Directorates of the Provincial Agriculture Departments. Farmers were to participate in project implementation through Water Users Associations

[10] Salinity Control and Reclamation Project (SCARP) of Pakistan, was financed with local resources and a variety of external financing, including IDA funds. The IDA has made 27 irrigation loans or credits to Pakistan for a total of US$1,305 million. Nine of these, or US$457 million, were principally for drainage to control Stalinization and water logging (World Bank, 2001).

that would replace informal farmer activities in the project areas. However, the radical change in institutional reform process came about on the initiative of the World Bank as discussed in the earlier section.

In 1995, the Government of Pakistan agreed to the World Bank proposal and envisaged a strategy under which Provincial Irrigation Departments (PIDs) would be transformed into autonomous Provincial Irrigation and Drainage Authorities (PIDAs) with regulatory functions, with canal commands managed by Area Water Boards and Farmers Organizations operating and maintaining irrigation and drainage systems at the distributary's level as well as at the minor and watercourse levels (Vander and Edward, 1998). Due to the great number of farmers involved, Farmers Organizations were to be tested in pilot areas. According to Rinaudo and Tahir, "the Government of Pakistan did not explicitly rule out the possibility of privatization, neither did it exclude the possibility to create tradable water rights that would be de-linked with the land."

In negotiations between the donors and the Government of Pakistan over a draft of the new legislation, the Provincial Irrigation Departments flatly rejected the privatization of the canal system and the separation of water from the land so that the former could be sold or traded as a commodity. Even after the then President of Pakistan declared that there would be no such privatization, the criticism continued because "It was evident by this time that opposition to the reforms was now wide-spread and deeply rooted among the national farmers' organizations dominated by large and influential landowners, provincial and national politicians, the officials of the provincial irrigation departments, and professional societies".

A coalition against privatization emerged between large influential farmers and many small subsistence farmers; the latter joined the protest in the absence of any organized effort to inform them about the content and objectives of the proposed reform. The Government of Pakistan in response to the protests modified the PIDA draft legislation that gave rise to disagreements between the donors and the Federal Government. While the latter perceived the draft legislation, was the best under such circumstances, the multilateral lenders criticized it as too narrow because it focused only on the transformation of PIDs into PIDAs, not on the irrigation sector as a whole.

Ultimately, the Government of Pakistan was confronted with the conditionality set by the World Bank and the Asian Development Bank that far-reaching legislation had to be adopted before the loans were finalized. In the end, an agreement was endorsed by the Government of Pakistan, including the President, the Prime Minister, the four Provincial Chief Ministers, Cabinet officials and the lenders, at the highest political level. However, the commitment of the Provinces was crucial because according to the constitution, only the Provincial Governments and Assemblies are entitled to modify irrigation management, not the Federal Government. In June 1997, the Punjab Irrigation and Drainage

Authority Act was enacted by the Provincial Government of Punjab; other provinces followed. While the Punjab ordinance specifies the powers and duties of PIDA, it requires the Government of Punjab to establish Area Water Boards and Farmers Organizations, and to assign such power and functions to them as it may deem fit. The selection of pilot areas for initial reform implementation and the powers assigned to Farmers Organizations were a matter of continuous contention, as was the cooperation between PID's staff and Farmers Organizations in the pilot areas.

Although there has been strong commitment to the reform at the highest political levels, including the first appointed Managing Directors of PIDA, implementation of the reform has progressed only slowly. There are several reasons that can be attributed to delayed implementation including; supply-oriented mentality of policy makers, fragmented administrative structures and lack of coordination among the administrative entities. Potential corruption among the irrigation officials is also possible as there is no transparency or accountability in the system. Moreover, institutional reforms pose a threat to the status quo of elites, making significant reforms even more difficult. This is why the means for enhancing water use efficiency and sustainable water development and management still await implementation.

CONCLUDING REMARKS

In Pakistan, institutional reform has affected several participants, who perceived the World Bank-proposed reform package as a threat to their established interests. The most pronounced opposition to the modified reform package came from large and powerful landlords, as well as from irrigation department officials. While the former were reluctant to share water and saw the perceived reform as a threat to their economic and political power, irrigation bureaucrats with financial ties to these interests had benefited from the anti-reform status. The PIDs as a whole has to change: staff from Irrigation Departments are faced with financial constraints, transparency and accountability, thus losing power, authority and rent-seeking opportunities.

Although there has been strong commitment to the reform at the highest political levels, nevertheless, implementation has been slow. Supply-oriented mentality of policy makers, fragmented administrative structures, lack of coordination among the administrative entities and potential corruption in the water sector are the main reasons for the delay in implementation.

REFERENCES

Bandaragoda, D.J. 1996. Institutional conditions for effective water delivery and irrigation scheduling in large gravity systems: evidence from Pakistan. In: *Irrigation Scheduling: From Theory to Practice,* Proceedings ICID/FAO Workshop, Sept. 1995, Rome. Water Report No. 8.

Bandaragoda, D. J.; and S. U. Rehman. 1995. Warabandi in Pakistan's canal irrigation systems: Widening gap between theory and practice. IIMI Country-Paper Pakistan No. 7. Colombo.

ICID, 2005. Country Policy Support Program Report on 'Basin Level Assessment and National Consultation, Lahore, Pakistan.

Kahlown M;Akram, and Majeed Abdul (2001). 'Water Resources Situation in Pakistan: Challenges and Future Strategies" http://www.comsats.org.pk/latest/m_akram_kahlown.pdf.

Neubert, S.W; Scheumann, A. V.; Edigg (2002) Reforming Institutions for Sustainable Water Management, German Development Institute. Bonn, Germany.

North, D. C. (1990). "Institutions, institutional change and Economic Performance". New York: Cambridge University Press.

Ostrom, E. (1986): An agenda for the study of institutions. *Public Choice* 48: pp. 3–25

Pakistan Agricultural Statistics, Government of Pakistan, 2003.

Population Action International, Sustaining Water: Population and Future of Water Supplies, Washington, DC. 1993.

Pakistan Water Sector Strategy (PWSS), 2002 "National Water Sector Profile, Volume 5", Ministry of Water and Power, Islamabad, Pakistan.

Rinaudo, J.D. and Z. Tahir (1999): The political economy of institutional reforms in Pakistan irrigation sector, Cemagref Working Paper No. WP 99-02, Montpellier.

Saleth, R.M; Dinar, A. 1999. *Evaluating water institutions and water sector performance.* World Bank Technical Paper No. 447. Washington, D.C.: World Bank.

Saleth, R.M.; Dinar, A. 2000. Institutional Changes in Global Water Sector: Trends, Patterns, and Implications. *Water Policy,* 2(3):175-199.

Sustaining Water – Population and the Future of Renewable Water Supplies, Population Action Welfare, 1993.

Vander Velde, Edward J. 1998. Progress in participatory irrigation management in Pakistan: a report on pilot projects in farmer organization at the secondary canal level. Consultant's Report. The Asian Development Bank. Manila, Philippines.

WAPDA "Pakistan's Vision of Water Resources Management", Pakistan Development Forum, 2003. Minister's PowerPoint presentation is available at http://lnweb18.worldbank.org/sar/sa.nsf/Attachments/PDF2003-W&P/$File/W&P.pdf

World Bank, 2001, Pakistan - SCARP Transition Pilot Project, Independent Evaluation group, Washington, DC.

World Bank, 2005, Pakistan Country Water Resources Assistance Strategy, Water Economy: Running Dry. Agriculture and Rural Development Sector, South Asia Region, Report No. 34081-PK

MATCHING IRRIGATION SUPPLY AND DEMAND IN EGYPT

Dr. Ragab Abdel Azim[1]
Eric Viala[2]

ABSTRACT

The proper assessment of water needs is a critical step towards water use efficiency. This is especially true in Egypt where the unique source for water resources is Egypt's share of the Lake Nasser reservoir, behind High Aswan Dam (HAD). Volumes of water have to be released from HAD in a timely manner in order to satisfy the needs of water users, mostly irrigating farmers.

Until the mid-1990s, irrigation demands were known with some accuracy since Egyptian farmers were organized to grow prescribed crops. Since then, the Government of Egypt has progressively freed them from any obligation, and farmers are now able to individually choose their cropping patterns. While this has resulted in significant increases in yield and farming incomes, it has also complicated the task of the Ministry of Water Resources and Irrigation (MWRI): the MWRI now would release water from Lake Nasser based on "indicative" cropping patterns and calendars. This sometimes resulted in a significant "mismatch" of supplies and demands with water volumes not being available to farmers when needed, or eventually flowing to the Mediterranean Sea without being utilized.

This has led the MWRI to design and implement a routine and systematic collection of crop information from farmers (through the Ministry of Agriculture and Land Reclamation, MALR) to the MWRI. This system is known as MISD, Matching Irrigation Supplies and Demands. It has been developed in the late 1990s with technical assistance from USAID. This paper highlights the MISD process, components, issues and suggestions for improvement.

INTRODUCTION

Egypt's water supply relies almost exclusively on the Nile through the huge reservoir behind the High Aswan Dam: Lake Nasser. Out of an annual Nile inflow of about 84 billion cubic meters, Egypt's share is set by international agreement with Sudan at 55.5 billion cubic meters. Alternative water sources are limited and

[1] Senior Director of Works, Distribution Central Directorate, Ministry of Water Resources and Irrigation, Cairo, Egypt
[2] Senior IWRM Resident Advisor, USAID-funded LIFE-IWRM Project managed by International Resources Group, Cairo, Egypt – eviala@iwrmeg.org – eviala@irgltd.com

involve erratic and meager precipitations (average annual rainfall being less than 2 inches over most of the country), fossil groundwater whose extraction is a "one-time shot", and still expensive and underdeveloped desalination technologies.

The demand for fresh water resources has, on the other hand, steadily increased over the years, along with the population growth and industrialization, thus reducing the per capita share. Egypt recently became a water scarce country (i.e. with less than 1,000 m3/capita/year). Facing the challenge of increasing water demands with limited options to increase the supply, the MWRI has taken steps towards better water management. Concepts such as water savings and water use efficiency have now become planning priorities if not yet management objectives.

The allocation of water resources at national level relies on appropriate releases from HAD. Since there is limited storage capacity all along the Nile River, the volumes released will make their way downstream and eventually reach the Mediterranean Sea after a dozen days or so. Overestimated volumes will get lost to the sea[3] while underestimated volumes cannot be augmented in any way. This means that water use efficiency relies first on a proper assessment of what the water requirements are.

Until the mid-1990s, irrigation demands were known with some accuracy since Egyptian farmers were organized through Agricultural Cooperatives and forced to grow prescribed crops. The MWRI previously released water from the HAD based on the cropping patterns planned and implemented by the MALR. In the mid 90s, a liberalization effort was carried out by the Government of Egypt in order to free farmers from centrally planned constraints (agricultural prices, mechanisms for input purchase and crop sale, and notably choice of cropping patterns).

While this has resulted in significant increases in yields and farming incomes, it complicated the task of the MWRI which now had to rely on "indicative" cropping patterns to plan the releases from HAD. MALR field agents would still assess the expected cropping patterns at the beginning of the season, but with much less accuracy. Weather conditions, market prices, and input availability (among other factors) could also lead farmers to change their plans. This resulted in a significant "mismatch" of supplies and demands with water volumes not being available to farmers when needed, or eventually flowing to the Mediterranean Sea without being utilized.

Both Ministries acknowledged the need for a routine and accurate transfer of cropping information from farmers through the MALR to the MWRI. The MISD

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[3] From a purely economic or human-centered point of view, these volumes are lost. But of course volumes of fresh water from the Nile River are essential for the ecological equilibrium of the coastal areas, coastal lakes and Mediterranean Sea.

program was developed a few years ago with that specific objective: a better evaluation of real-time irrigation water demands in order to match these with actual water deliveries. The MISD program has been described as a significant step toward demand-driven irrigation management and water use efficiency.

MISD PROCESS AND ACHIEVEMENTS

The MISD system was developed by the MWRI in the late 1990s with technical assistance from USAID. It is based on:

1. Cooperative links between the MALR and MWRI at local (district) level.
2. Agricultural data on cropping patterns and schedules being collected twice each month (at the first and middle of the month) by MALR field extension agents. This agricultural data is aggregated for each branch canal command area within the boundaries of the MWRI irrigation district and provided to the MWRI district engineer.
3. A computer program that allows the processing of the agricultural data and its translation in terms of water demands (at district level).
4. Agricultural data and water demand information being forwarded from the district through the (regional) Irrigation General Directorate to the MWRI Central Directorate for Water Distribution (CDWD) in Cairo for scheduling water releases from the HAD.
5. The water allocation schedule being prepared and communicated back to the Irrigation General Directorate, and to the MWRI district engineer.
6. Information on water availability and distribution being communicated by the district engineer to MALR agents and to farmers within the district.

Twice a month, MALR field agents determine the existing area for each major crop[4], for all other crops as one category, and for fallow land (not irrigated) in their area. At the same time they also determine crop areas expected for the next half-month period using the same categories. This cropping information is provided to the MWRI district engineer. Using a database or Excel spreadsheet, the district engineer calculates the biweekly water requirements as follows:

$$WR = (Ac \times WD) / \mu$$

where:

Ac is the cropped areas (feddans)

WD is the standard water requirement, which depends on the crop, the month, and the region (these values are standardized for Egypt, they have been calculated using climatic data and the FAO guidelines).

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[4] Major crops are defined as those that occupy large areas and have significantly higher water requirements, such as rice and sugarcane. They may differ from district to district.

μ is the standard water distribution efficiency (combines canal delivery & irrigation application efficiencies). For lack of actual data, it is taken as 0.7 in Egypt, regardless of actual canal, topographic, soil, climatic conditions and irrigation practices.

These biweekly water requirements are aggregated for the entire district and sent to the MWRI's headquarters. There they are used to plan the releases from HAD, taking into consideration the proper time lags for the released volumes to timely meet the needs along the Nile valley (see map in figure 1):

1-2 day to reach Esna Barrage;
3-4 days to reach Naga Hammadi Barrage;
5-6 days to reach Asyut Barrage, and
9-10 days to reach Cairo and then the Delta.

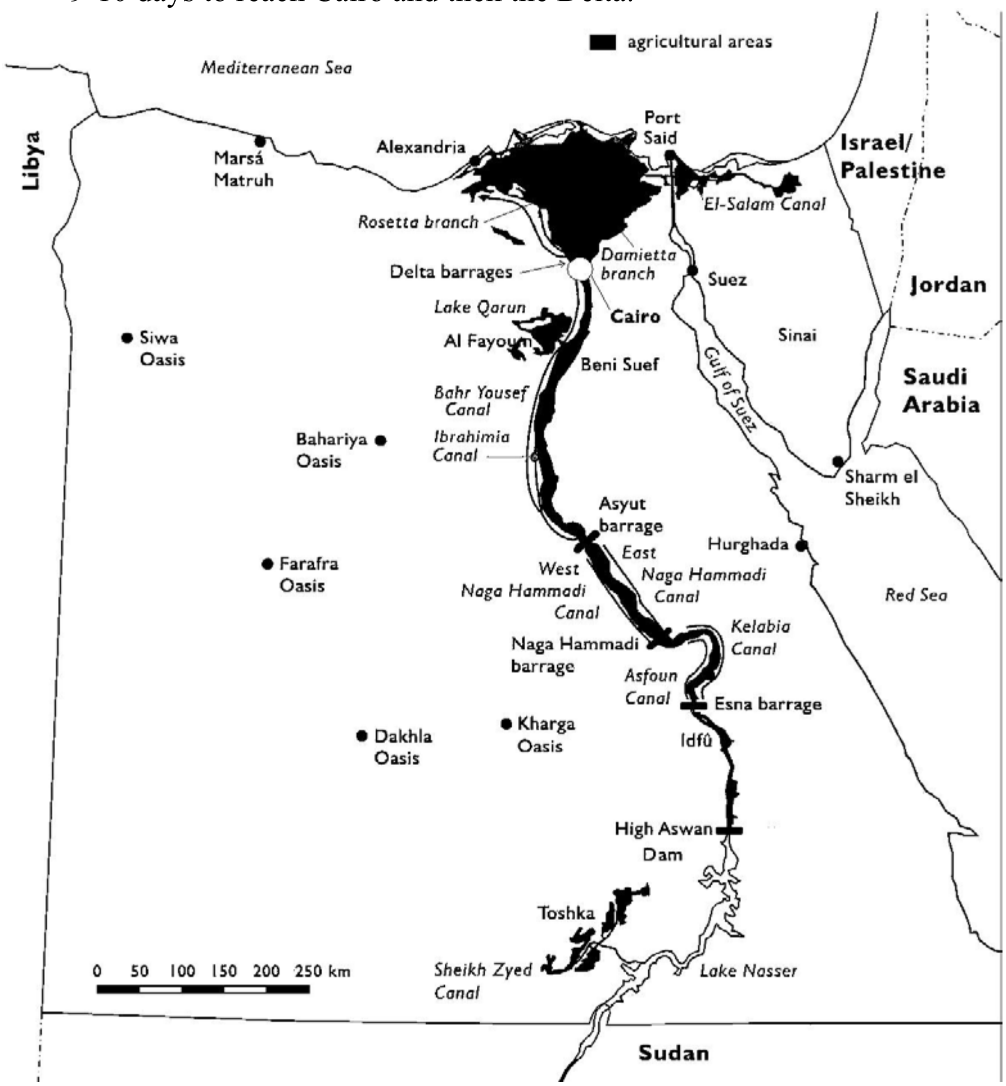

Figure 1. Map of the Nile Valley.

The LIFE-IWRM[5] Project (hereafter defined as the Project) has been supporting the implementation and strengthening of the MISD program in all 27 Integrated Water Management Districts (IWMDs) established by the project (covering 15% of the irrigated area of Egypt). Significant project achievements to date include:

- Excellent collaboration between MALR and MWRI;
- The data collection effort being carried out on a routine and systematic manner in all IWMDs;
- IWMD managers being able to translate the crop information into biweekly water requirements and thus know their district water needs; and
- Biweekly water requirements being communicated to the CDWD in Cairo every two weeks.

The main success of the MISD program is the fact that at national level, about half of the districts (one hundred or so) routinely evaluate and send their water needs to the CDWD. This major data collection effort is essential and significantly contributes to plan the proper releases from HAD. Another significant impact is that through the MISD process, IWMD managers and engineers have been sensitized to the demand side of water management. They also became aware of the limited amount of water resources available in Egypt, and the need to use them efficiently.

MISD ISSUES AND POTENTIAL IMPROVEMENTS

The MISD process, as designed but most importantly, as implemented, suffers from several issues:

- Inaccuracy of the cropping pattern information;
- Inaccuracy of the cropping area information;
- Inaccuracy of the calculation of water needs;
- Limited understanding of the actual routing of the released volumes and their matching with water needs (and thus limited capacity to optimize the releases);
- Lack of information to local (district) MWRI managers on the supply to be expected, in order for them to plan and optimize the distribution; and
- General lack of feedback and monitoring for the process to improve over time.

Adequacy of crop information

The accuracy of the crop information depends on the MALR field agent's ability to adequately identify the current cropping pattern and forecast the cropping pattern expected two weeks in the future based upon existing crops, knowledge of the farmer's practices, and direct contact with farmers. This data collection effort

[5] LIFE (Livelihood Incomes from the Environment) is a USAID-funded program in Egypt which includes other projects besides the Integrated Water Management Project.

is not necessarily the most important task assigned to the MALR field agent. Even though cooperation is usually good at field level, the usual (political) antagonism between agriculture and irrigation agencies also undermines the effort.

It is foreseen that in the future, the Branch Canal Water User Associations (BCWUAs) being now established by the project will be tasked to carry out this data collection effort, with technical support from MALR and MWRI. The crop information would be of better quality since farmers have a vested interest in seeing their water needs properly addressed.

Accuracy of cropping areas

Cropping areas are rarely known with accuracy, and often over-estimated for the following reasons:

- The cadastral maps (scale 1/2,500) are more than 20 years old and thus outdated, especially considering the development of urban areas all along the Nile;
- Both MALR field agents and MWRI are afraid to be held responsible by farmers for water shortages and thus tend to over-estimate cropped areas;
- Farmers recognize queries regarding their landholding as being related to the collection of the land tax; they are understandably vague or misleading in the information they provide.

Remote sensing is the generally suggested solution to provide information regarding cropped areas. It has however a significant cost, chiefly for the purchase and processing of adequate satellite images. While the project is supporting some pilot activities in that direction, a simpler decentralized assessment has also been promoted. The measurement of actual cropped areas is done by MWRI field staff:

1. Using the old cadastral maps as initial mapping support;
2. Recording, in the field, with GPS devices, the boundaries of cropped areas; and
3. Calculating cropped areas with a simple digital mapping software such as AutoCAD.

Evaluation of water needs

The third issue is the translation of cropped areas and cropping patterns into water requirements. The standard water requirements are reasonably valid since they are based on regional climatic data and are tailored to the type of crops and the month of the year. They could however be improved through actual field measurements. The most significant source of inaccuracy is the use of the same standard irrigation efficiency everywhere, regardless of actual canal, topographic, soil, climatic conditions and different irrigation practices.

A first step for tailoring this efficiency factor would be to identify different regional values through the consideration of canal, soil and climate characteristics along with irrigation management and application techniques. A second step would be again to conduct field measurements to better define regional or local efficiency values. For the time, this is being beyond the scope of the project although local flow measurements are being carried out at district-level and could be used to that end (see hereafter).

Operational optimization

The fourth issue relates to the actual routing or downstream propagation of the releases. The MWRI collects real-time water level information on more than a hundred sites along the Nile. The CDWD should use this information to:

- First better understand when and how the released volumes reach different points along the valley (the magnitude of the releases, the contribution of return flows and drains, and the levels of the Nile River are all factors that impact the routing); the aggregation of all individual (district) water needs into a water requirement schedule and the planning of the releases would become more accurate;
- Second optimize the operation of the several barrages along the Nile to somewhat augment or delay the flow[6]; this can simply be done through monitoring and experience; and
- Third possibly develop a DSS model to manage HAD and the other barrages along the Nile River.

These activities are beyond the scope of the project but could be implemented by the MWRI, given central level commitment and the allocation of resources (and possibly external technical assistance in the case of a DSS model).

Distribution information

The fifth issue is the fact that little information is provided back to regional and local MWRI managers as to how much water they will receive for distribution. This is actually an issue with the way the MISD program is implemented. There is limited intent to convey information back to the local level for several reasons:

- From the perspective of central MWRI managers, the data provided by each district is not considered as an allocation request; the MISD program is simply seen as a bottom-up data collection effort to plan the water releases from HAD;

[6] Currently the operation principles are the following:

- In summer, the barrages are kept at their maximum water level, so as to allow some augmentation of the flow if needed to prevent shortages;
- In winter, the barrages are kept at their minimal water level, so as to allow some reduction of the flow if needed to prevent flooding.

- There is limited flow monitoring, only on critical locations along the Nile and main canals, and thus limited understanding of when and how the released volumes will eventually reach different points along the valley; and
- Centralization still prevails, with limited delegation to lower levels; providing distribution information downward is not yet an innate inclination.

The Project is not only training district engineers to prepare and submit biweekly water requests, but has also been supporting a flow monitoring effort that allows the calibration of water structures and thus a regular translation of water levels into actual discharges. MISD requested volume and actually received supply can thus easily be compared to each other at district level.

Lack of monitoring

A critical design flaw is the absence of monitoring activities within the MISD program: the process as currently implemented actually stops with the planning of the releases. The actual matching of supplies and needs is somewhat measured at central level, but not at regional or local level. The accuracy of the data provided is not cross-checked either..

But without feedback, the MISD program cannot learn from experience, and cannot develop from a conceptual exercise to an actually ground-truthed management process. A typical example is the system constraints, such as insufficient canal capacity: even if the proper volumes are released, they cannot be conveyed on time to address the needs.

As mentioned earlier, the Project has been supporting a flow monitoring effort that allows the calibration of water structures and thus a regular translation of water levels into actual discharges. Water needs and actual deliveries can thus be compared. In parallel, several monitoring activities have been developed and are being implemented at district-level:

- Recording and follow-up of complaints registered by water users;
- Recording and follow-up of violations committed by water users and residents; and
- Annual farmer satisfaction survey (about 200 farmers are asked through a short questionnaire to grade the water delivery service they receive).

CONCLUSION

The MISD program is intended to address what the MWRI has identified as specific situations that give rise to mismatching. These can be grouped into three general categories:

1. *Under- or over-estimating crop water demands under free cropping choices*, including cropping patterns and calendars.
2. *System constraints*, such as canal capacity, system storage capacity, and lag time between water releases from HAD to the farm.
3. *External factors*, such as precipitations, unseasonable temperatures and unanticipated drainage water reuse.

The MISD program as implemented only addresses:

- The first issue to some extent, but with serious accuracy concerns (notably regarding actual cropping areas and irrigation efficiency);
- The system constraints inadequately without regular monitoring and feedback; and
- The external factors incompletely without proper operational procedures being defined and used.

The Project attempts to address some of the technical issues identified with the MISD program, notably by decentralizing the process: the evaluated water requirements can now be compared at district-level to the actual supplies and thus used by the MWRI district engineer to manage and allocate the water resources being received.

But the concept and the implementation process of the MISD program need also to be reviewed. From the perspective of MWRI managers, the MISD Program was designed as a tool for central planning, with a bottom-up data collection effort feeding into the decision-making regarding releases from HAD. As usual with such approaches:

- Local level data collectors have limited incentive to improve the accuracy of the data they collect and transmit since they are not necessarily aware of the objectives of the exercise, and do not get much feedback (nor praise) for their efforts; and
- Central level managers cannot assess or improve the quality and accuracy of the data they receive.

Such concerns cannot be tackled through technical fixes. The MWRI should promote accountability and decentralization by (see also Figure 2 next page):

1) Requesting central managers to:
    a. Communicate the release plans they decide on and implement;
    b. Monitor how the releases actually match the needs;
    c. Collect and use feedback from the field to improve their decision-making process;

2) Improving the awareness of district managers and field staff regarding:
   a. The need to be more efficient in its water use;
   b. The concept of balancing demand and supply;
   c. The MISD process and the need for accurate data; and
   d. The need for measuring and comparing demands and actual deliveries.

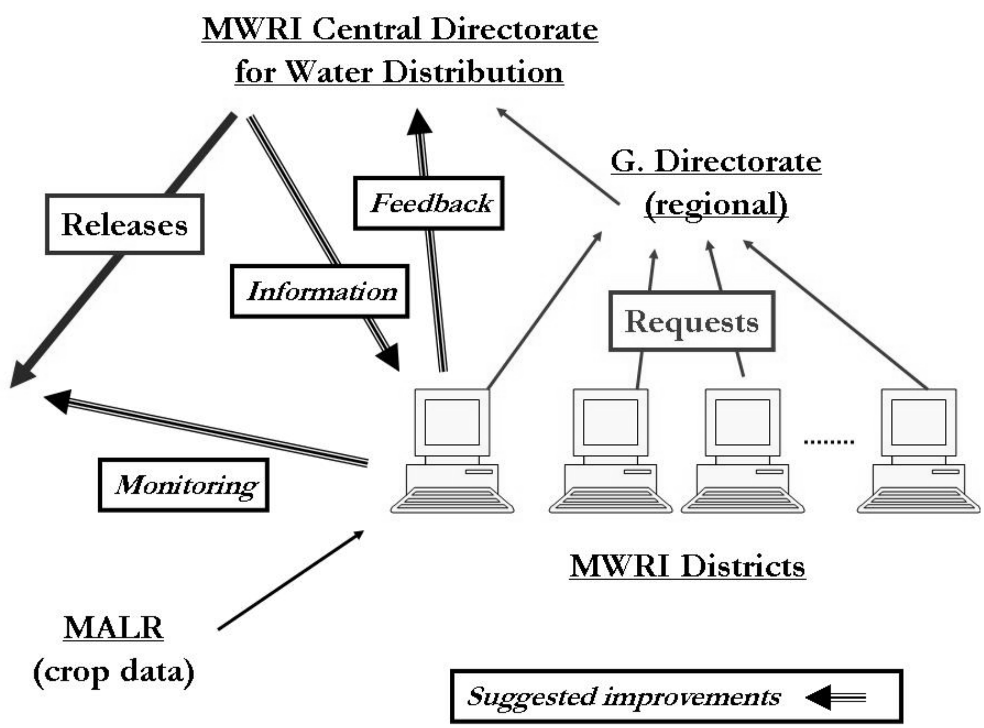

Figure 2. Improved decentralized MISD process

It is only through this kind of institutional/behavioral change that the MISD program can effectively contribute to better water use efficiency and become an important step toward an efficient, demand-driven irrigation system.

REFERENCES

"Reducing mismatch of irrigation deliveries" and "Matching irrigation supplies and demands", Water Policy Program Reports no 33 and 55, 2000-02

LIFE-IWRM Project, Monitoring & Evaluation Plan, International Resources Group, 2005

DROUGHT RISK MANAGEMENT FOR IRRIGATED POTATO PRODUCTION IN IDAHO

Bradley King[1]
Jeffrey Stark[2]
Stephen Love[3]
Christopher McIntosh[4]

ABSTRACT

Streamflow in much of the western United States originates as snowfall that has accumulated in the mountains during the winter and early spring. During periods of drought, the water supply for a large portion of irrigated cropland in Idaho is at risk of depletion before the growing season ends. In the case of irrigated potato production, early depletion or limited availability of irrigation water can result in substantial financial loss to a producer due to reduced yield and quality and difficulty in harvesting, handling and storing the raw product. Basin wide estimates of available water supply are provided by Federal and State agencies, however, a given producer's irrigation water supply can be vastly different due to water rights based on the Doctrine of Prior Appropriation, which allocates water according to a priority date. To minimize financial risk under drought conditions, potato producers need realistic estimates of available water supply well in advance of the growing season and production management guidelines for economical potato production under limited water supply. To address this need, a methodology for estimating the probability of a water supply shortage that incorporates water right based allocation was developed to assist producers with drought risk management planning. Additionally, the drought tolerance of six commercial potato varieties was evaluated for four widely varying seasonal drought management patterns simulated by irrigation management. The methodology developed to estimate probability of a water shortage on an irrigation district basis is described and results of an economic risk analysis for the six potato varieties subjected to the four drought management patterns is presented. The results show that the probability of a water shortage can vary widely among irrigation districts due to differences in water priority dates. The results of the economic risk analysis show that potato variety selection and

[1] Agricultural Engineer, USDA-ARS NWISRL, 3793 N. 3600 E., Kimberly, ID 83341-5076; bking@nwisrl.ars.usda.gov. Formerly Associate Research Professor, University of Idaho.
[2] Professor of Agronomy, Dept. of Plant, Soil and Entomological Sciences, University of Idaho, Idaho Falls, ID; jstark@uidaho.edu.
[3] Extension Horticulturalist, Dept. of Plant, Soil and Entomological Sciences, University of Idaho, Aberdeen, ID; slove@uidaho.edu.
[4] Professor, Dept. of Agricultural Economics and Rural Sociology, University of Idaho, Idaho Falls, ID; mcintosh@uidaho.edu.

irrigation management strategy can substantially reduce economic loss in potato production systems during drought.

INTRODUCTION

Annual streamflow in much of the western United States originates as snowfall that has accumulated in the mountains during the winter and early spring. Runoff from snowmelt in combination with reservoir storage provides the surface water supply for nearly 1.2 million acres of cropland in southern Idaho. However, certainty of the quantity of snowmelt runoff and river basin reservoir storage isn't available until the first of July when snowmelt is complete and the growing season is 2-3 months along. A shortage in the surface water supply affects long season crops the most (e.g. potatoes, sugar beets, corn) as the water supply is exhausted in early to mid-August in drought years. A producer's ability to manage drought risk is largely dependent upon knowledge of the water supply prior to the growing season. This knowledge can have a substantial influence on the crops and varieties to be grown, the number of acres to be planted and the estimated operating capital requirements. Water supply information needs to be available promptly so that production management decisions can be made without delay to minimize financial risk.

Water rights in Idaho and most western states are based upon the Doctrine of Prior Appropriation, which in essence means, "First in Time is First in Right." As plans for irrigated areas developed, water rights were sought and granted once water was actually applied to the land. As storage reservoirs were planned, water rights were applied for and granted once the dams were completed. Concurrently, reservoir storage space was sold with storage water rights assigned priority according to the water rights of the storage reservoir. The result of over 100 years of water resource development is a multitude of water diversion and storage rights based on a myriad of priority dates. Thus, the allocation of water during drought years depends upon water right priority dates as much as the available supply. An irrigation district's total water supply availability depends upon its natural stream flow priority date(s) and its water storage priority date(s) in relation to other water right holders, be they agricultural, municipal, industrial or environmental uses.

The objective of this project was to develop a methodology for estimating risk of a water supply shortage for irrigation districts and evaluate drought tolerance of common potato varieties for use in making production management decisions that minimize financial risk in potato production systems. The methodology used to estimate risk of a water supply shortage for an irrigation district and results of potato drought tolerance evaluations are described.

Evaluating Water Supply Risk for an Irrigation District

The USDA NRCS in western states publishes monthly basin outlook reports January through June based on data collected from federal-state-private cooperative snow surveys (www.wcc.nrcs.usda.gov/cgibin/bor.pl). The snow survey data are used by hydrologists to estimate monthly runoff flows that will occur when the snow pack melts. These forecasts are coordinated between hydrologists in the USDA NRCS and NOAA National Weather Service. These forecasts are an important part of risk management planning as they define water availability basin wide but they do not account for the differences in water allocation between irrigation districts due to water rights.

River Basin Reservoir Storage: In a river basin with snowmelt hydrology and reservoir storage, the reservoirs capture base flow and snow melt runoff above minimum stream flow requirements or until reservoir storage water diversion rights are filled. This is also subject to storage space required to safely pass peak snowmelt runoff events. Under drought conditions, partially filled reservoirs are managed to capture as much water as allowed by the reservoir storage water right. Thus, reservoir storage for the coming irrigation season is a function of flow and snowmelt runoff, which for Idaho is normally completed by July. This storage is called initial storage to denote it from storage that occurs after the irrigation season and before Oct 31st. Total storage for the irrigation season is the sum of initial storage and carryover from the previous year defined as reservoir storage on October 31st of the prior year.

Under drought conditions, initial storage is largely a function of April through September basin runoff or streamflow. As an example, initial storage for drought years in the Upper Snake River Basin of Idaho is shown in figure 1 as a function of April through September basin runoff volume. The data shown in figure 1 represents nine years during the period of 1980 through 2003 that basin reservoir storage did not fill to capacity. The relationship between initial storage and April through September basin runoff volume is well represented by a linear function having a correlation index (r^2) of 0.911. Thus, total basin storage can be reasonably well estimated as a function of April through September basin runoff plus carryover storage from the previous year. If the sum is greater than total basin reservoir storage, then the reservoirs should fill and the irrigation water supply will be sufficient.

The linear relationship shown in figure 1 provides a good estimate of initial storage on average; however, there is still uncertainty about the actual value of initial storage for a given level of basin runoff. The uncertainty in initial basin storage volume is due to uncertainty in how much snowmelt will enter streams; which depends upon the rate of snowmelt, soil moisture conditions, and spring precipitation. This uncertainty needs to be quantified in order to measure risk related to the available water supply. One approach to quantify this uncertainty is to use the prediction interval for the linear relationship (Lott 1984). The prediction interval for initial basin storage using a 95% confidence interval is shown in figure 1. As an example, if April through September runoff volume is 4.2 million ac ft, then initial basin storage is between 2 and 3 million ac ft with 95% confidence.

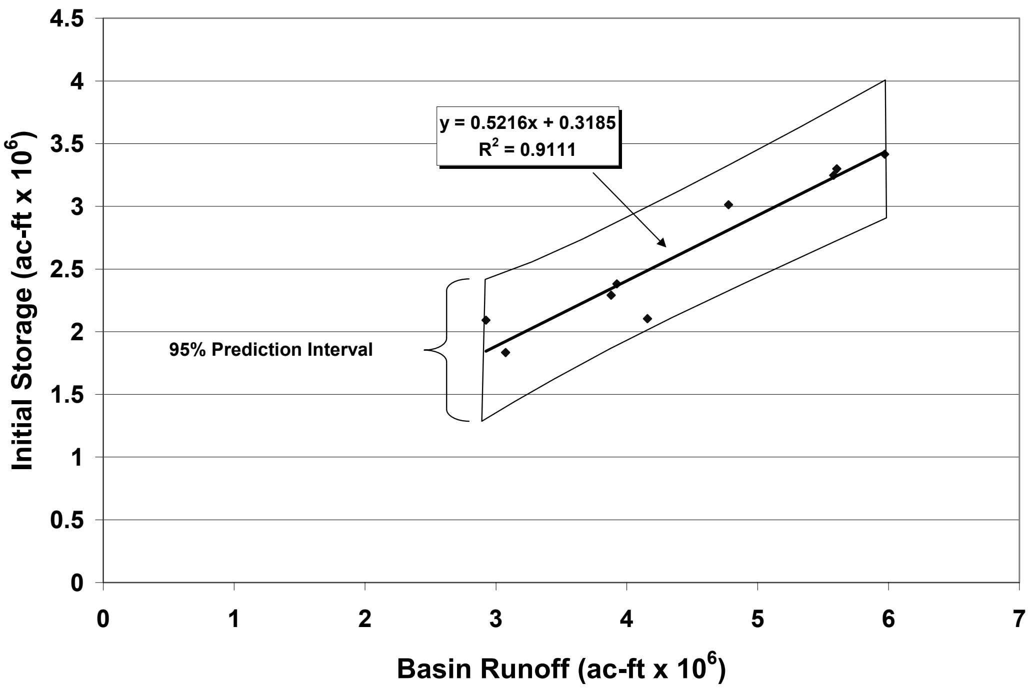

Figure 1. Basin initial storage as a function of basin runoff for 9 of the 24 years (1980 – 2003) river basin storage did not fill to capacity along with 95% prediction interval.

Irrigation District Storage Allocation: Water allocated to an irrigation district depends upon the initial storage captured in the reservoir(s) in which it has purchased storage right(s) plus any unused storage from the previous year subject to the upper limit of the storage space purchased. Initial storage captured in a particular reservoir is dependent upon the storage water rights of the reservoir and the rate at which snowmelt occurs. This uncertainty is considered small in relation to the uncertainty in total basin storage. Thus, irrigation district storage allocation is considered to be a deterministic linear function of total basin storage only and is irrigation district specific.

Irrigation District Storage Requirement: Storage water required by an irrigation district to fulfill its irrigation demand after their natural flow water right is cutoff depends upon several factors. The most important factors are the priority date(s) of the natural flow water right(s), natural flow in the river (basin runoff), and crop water requirements for the season. The primary factor is basin runoff. The storage water requirement for the Aberdeen-Springfield Canal Co. as a function of basin runoff is shown in figure 2 as an example of irrigation district storage requirements. The linear relationship represents district storage requirements as a function of basin runoff reasonably well with a correlation index (r^2) of 0.85. The randomness about the linear regression line is due to randomness in seasonal water requirements due to crop mix, climatic conditions and snow pack melt

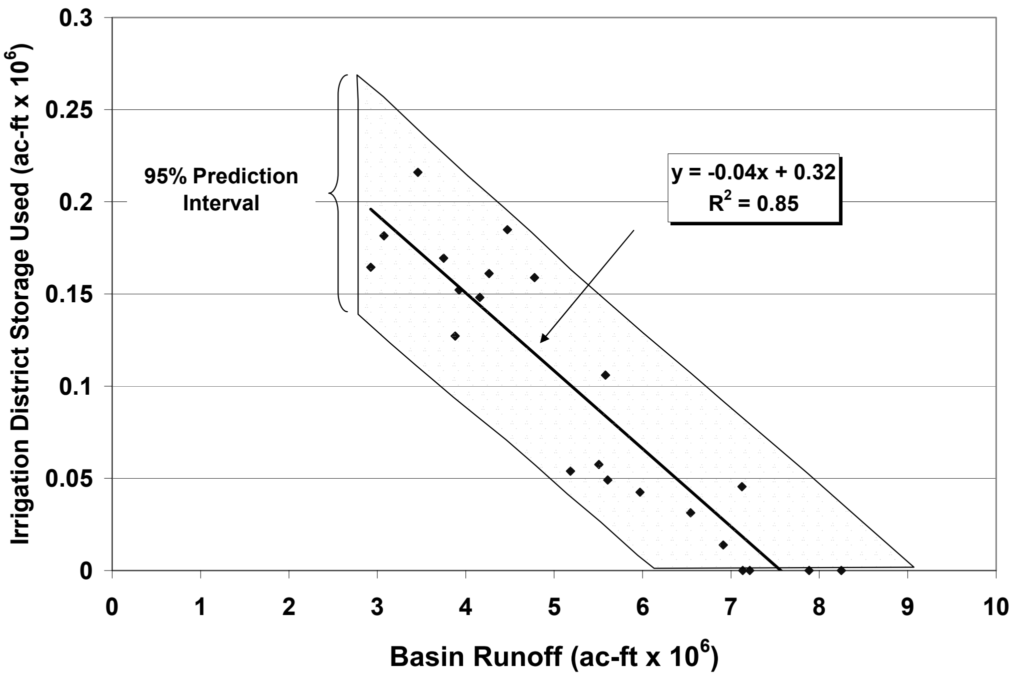

Figure 2. Storage water requirement and associated 95% prediction interval of the Aberdeen Springfield Canal Co. as a function of April through September basin runoff based 24 years of record.

pattern, which is also dependent upon climatic conditions. For example, if the spring is cool and wet, the snow pack will melt slowly and irrigation requirements will be delayed and reduced for the season. A slow snowmelt means natural flow will exceed irrigation demand longer into the growing season, delaying the time the irrigation district needs storage water and hence reducing storage water requirements. A warm/dry spring causes the opposite effect in terms of district storage water requirements. This uncertainty in storage water requirements is demonstrated in figure 2 using a 95% prediction interval for a linear regression relationship that is specific to the Aberdeen Springfield Canal Company.

<u>Calculating Water Supply Risk:</u> The risk of a water supply shortage, i.e. probability that water storage requirements will exceed allocation, is numerically calculated as the probability that an irrigation district's storage water allocation minus their storage water requirement will be less than zero. This representation of water supply shortage risk for a specific realization of basin runoff (conditional probability) is numerically calculated using the linear relationships and associated prediction intervals for irrigation district allocated storage and storage

requirement. At the lowest expected runoff volume, the probability of a water shortage is 1.0 or certain. At the highest expected runoff volume, the probability of a water shortage is zero. The cumulative risk of a water supply shortage is calculated by integrating the product of the conditional probability of a water supply shortage and the probability of the runoff event over the range of possible

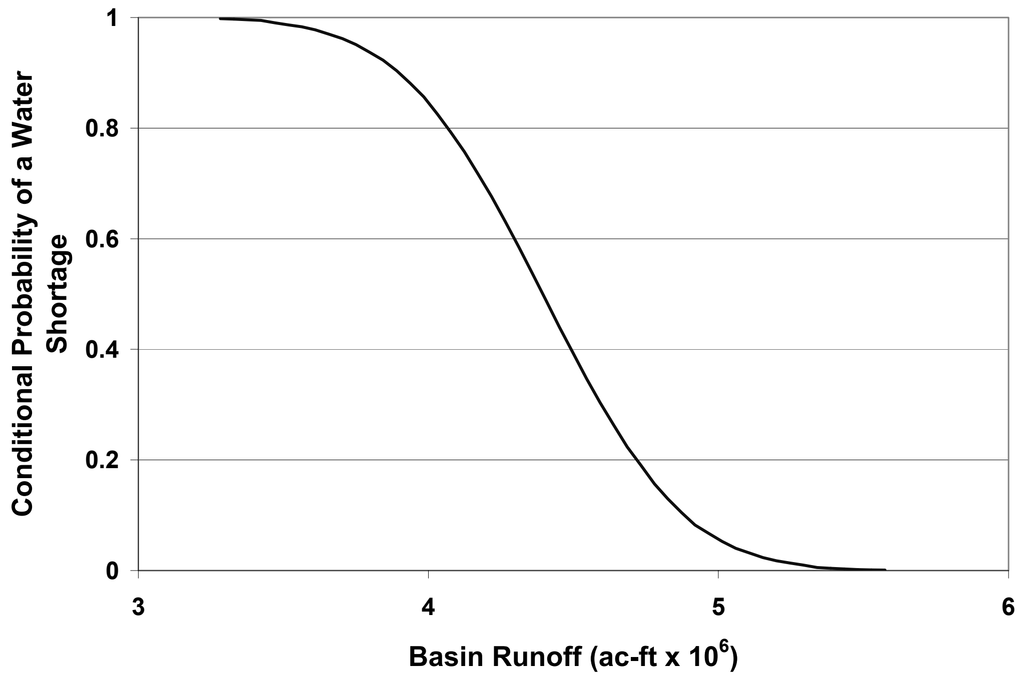

Figure 3. Conditional probability of a water shortage for Aberdeen Springfield Canal Co for February 2003.

basin runoff values. The probability of a specific runoff event is derived from the USDA NRCS April through September stream flow forecasts. An example of the computed conditional probability distribution function for the Aberdeen-Springfield Canal Co. is shown in figure 3. It assumes a basin storage carryover of 300,000 ac ft and February 2003 range in basin runoff forecast.

<u>Potential Water Shortage Severity:</u> Beyond quantifying the probability of a water shortage, the potential severity of the shortage also needs to be quantified. The potential severity of a water shortage is estimated as the maximum difference between the irrigation district's storage water allocation and storage water requirement regression lines. This maximum difference occurs at the minimum expected basin runoff estimate. This difference is then expressed as a percentage of the irrigation district's average annual total diversion to scale the potential water shortage severity to the particular district circumstances. Since the difference in regression lines or mean expected value is used to quantify severity of a water shortage, there can be a finite probability of a water shortage while the severity is zero. This results from using the prediction intervals about the

regression lines to compute probability of a shortage and mean values for computing severity of a shortage.

Examples of computed water supply risk and severity for a few select irrigation districts in Eastern Idaho for April 2004 basin runoff estimates and 2003 basin storage carryover are presented in Table 1. While all the irrigation districts have the same water source, there is a wide disparity in the probability of a water shortage and potential severity. This disparity is the result of water right priority dates, which determines allocation of natural river flow every day throughout the irrigation season. This disparity among irrigation districts demonstrates that the location of a producer's operation can have a substantial impact on water supply availability. The results emphasize the importance of including irrigation water rights in assessing the risk in water supply availability under drought conditions

Table 1. Computed water shortage probabilities and associated water shortage severity relative to average annual diversion for select irrigation districts.

Irrigation District	Probability of Shortage (%)	Severity (%)
Blackfoot	8	0
Burgess	71	10
Butte & Market Lake	33	38
Consolidated Farmers	63	20
Corbett	0	0
E. Labelle	22	0
Egin	21	0
Farmers Own	97	57
Harrison	52	12
Sunnydell	70	16

Estimating the probability of a water shortage is needed information, but it alone does not reduce risk. Production management decisions must be made accordingly to account for the possibility of a water shortage. One possible production management decision is to not plant potatoes if the possibility of water shortage exists. However, such a decision represents a financial loss (opportunity cost) if the water supply actually is sufficient for potato production. In this event, choosing not to plant potatoes does not maximize net return. Besides not planting potatoes, one possible management option is to choose a potato variety that is drought tolerant and will provide a reasonable yield and net return with reduced water application. Information for selecting potato varieties based on yield response to reduced water application is limited. For this reason a field study was conducted to evaluate yield response of six common potato varieties to reduced water application under Idaho climatic conditions.

Evaluating Potato Drought Risk

Six potato varieties were grown under five imposed widely varying seasonal drought patterns simulated by irrigation management in 2002 and 2003 to identify specific potato management systems that will minimize exposure to drought risk. The irrigation management schemes included: 1) application of irrigation water to provide 100% evapotranspiration (ET) replacement for the full season (100% Full Season), 2) providing 100% ET replacement until Aug 10 with no application thereafter (100% Early Cut Off), 3) providing 75% of ET replacement for the full season (75% Full Season), 4) providing 75% of ET replacement until Aug 10 with no application thereafter (75% Early Cut Off), or 5) providing 100% of ET replacement until July 20 with a reduction to 75% of ET until Aug 10 and then decreasing to 50% ET replacement until vine kill (Step Down). Irrigation was applied with a solid-set sprinkler system, while ET was estimated with the modified Penman method used by the U.S. Bureau of Reclamation AgriMet system (www.usbr.gov/pn/agrimet/). Each irrigation management scheme was applied to four 36 ft x 80 ft main plots comprised of six 12 ft (4 rows) by 40 ft variety subplots. The six varieties included in the study are Russet Burbank, Russet Norkotah, Alturas, Summit Russet, Ranger Russet and GemStar Russet.

An economic analysis was conducted to evaluate economic risk associated with each drought management scheme on the six commercial potato varieties. The specific budget used for evaluating the economic impact of drought as measured by the various drought management schemes are those constructed for Southeastern Idaho (University of Idaho 2003 Costs and Returns Estimates (Patterson and Smathers, 2003)). The costs and returns estimates used in the economic analysis are based on a model 1,500-acre farm with 500 acres in potatoes. The typical crop rotation is one year of potatoes followed by two years of grain. Corn may substitute for grain, while sugar beets and alfalfa are grown in longer rotations. The farm uses a center pivot irrigation system and surface water delivered from an irrigation district. The irrigation district charges a flat fee per acre for water.

The results of the economic analysis are summarized in figure 4 which shows the return to risk for each potato variety under each drought management scheme. For three varieties (Russet Burbank, Alturas, and Ranger Russet) a gradual reduction in water application as the season progressed was the best option. Russet Norkotah, an early maturing variety, had the smallest relative yield losses and highest returns to risk when irrigation was cut-off in early August (100% Early Cutoff), but showed significant drought susceptibility and lower returns when stressed throughout the growing season. GemStar Russet and Ranger Russet exhibited the highest degree of drought tolerance and highest returns to risk overall. By comparison, Russet Burbank showed a relatively high susceptibility to drought and low returns to risk in most limited irrigation management schemes, while Summit Russet and Alturas exhibited moderate drought susceptibility and would not be good choices for reducing drought risk. These data show that management options are available in terms of potato variety selection to reduce risk of economic loss in different drought management schemes.

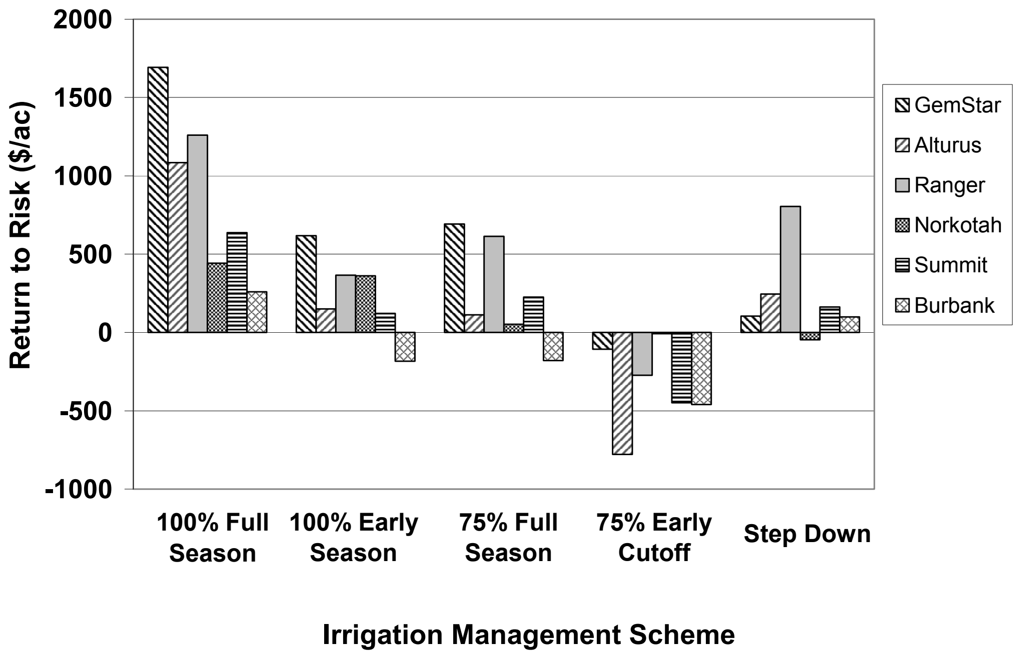

Figure 4. Calculated return to risk of six potato varieties under four imposed seasonal drought patterns compared to irrigation management to meet seasonal crop evapotranspiration requirements.

Dissemination of Potato Drought Management Information

Drought management information for potatoes is disseminated through the website: http://extension.ag.uidaho.edu/droughtpredict/. The information includes risk assessment of an irrigation water supply shortage on an irrigation district basis that is updated monthly January through April, potato variety drought tolerance comparisons, guidelines for irrigation and nitrogen management with limited water supply, and economic comparisons of water management strategies. Risk assessment for over 80 irrigation districts in the Upper Snake River basin and Boise River basin combined is provided on the website. These two river basins represent about 90% of potato production in Idaho irrigated by surface water supplies.

SUMMARY

Irrigation is required for the profitable commercial production of potatoes in Idaho. However, periodic drought is a fact of life, and can force producers to adopt sub-optimal irrigation practices due to restrictions on water availability.

Potatoes have a relatively shallow root zone and a lower tolerance for water stress than most other crops grown in Idaho. Drought management planning is necessary to minimize financial loss that can result from water supply shortages. Thus, producers need information on water availability for their production location and decision aids for adjusting agronomic practices under drought conditions.

An approach for estimating the risk of a water shortage and associated potential severity on an irrigation district basis was developed to assist producers with drought management planning. The approach requires a minimum amount of hydrologic information and incorporates an irrigation district's water rights into the estimates using historical water allocation and use data. Relative drought tolerances of six commercial potato varieties were evaluated under four different water restrictive irrigation management schemes. An economic analysis of yields for each potato variety under each irrigation management scheme used to simulate drought demonstrates the potential financial impact variety selection can have under drought conditions. These results show that choosing appropriate potato varieties and irrigation management strategies can substantially reduce risk of economic loss in potato production systems during drought.

ACKNOWLEDGEMENT

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REFERENCES

Lott, Lyman. 1984. Inferences related to linear regression and correlation. In An Introduction to Statistical Methods and Data Analysis, 280-324. Boston, Mass.: PWS Publishers.

Patterson, Paul E., and Robert L. Smathers. 2003. "South District Russet Burbank Commercial Potatoes: Fumigation and On-Farm Storage." EBB4-Po6-03, Department of Agricultural Economics and Rural Sociology, University of Idaho.

CASE STUDY — STATISTICAL FORECASTING TECHNIQUES FOR EVALUATING AN INTERRUPTIBLE SUPPLY CONTRACT

Rachel J. Kullman[1]
Karen R. Rademacher[2]
Stephen W. Smith[3]

ABSTRACT

In Colorado, unprecedented changes are brought to bear on senior irrigation water rights, primarily due to drought and population growth. Changes have created both pressures and opportunities to the irrigators who hold these senior water rights. Changing administrative procedures, escalating water values, and curtailment of ground water pumping in Colorado necessitate irrigators make hard decisions about how they will preserve their water supply and agricultural operations for the long-term.

In response to these changes, some irrigators in Colorado have explored options for "interrupting" their irrigation supply to provide water to a municipality or power company in exchange for financial compensation. These arrangements are often called interruptible supply plans or contracts. These contracts typically include guarantees that an irrigator will provide some portion of their water supply to the contracting entity. Despite the opportunity for financial compensation, many irrigators chose not to enter into such contracts because interrupting water supply can be uncertain and risky.

The case study presented in this manuscript provides an example of one statistical methodology that can be used to determine the level of risk or uncertainty associated with entering into an interruptible water supply contract. Understanding the risk and uncertainty can help both contracting entities understand the implications of an interruptible supply contract. The methodology, known as Monte Carlo simulation, is widely applied across multiple disciplines. However, we are not aware of its use in previous interruptible supply analyses.

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[1] Rachel Kullman is a project manager with Aqua Engineering, Inc. in Montrose, Colorado. rkullman@aquaengr.com
[2] Karen Rademacher is a project manager with Aqua Engineering, Inc. in Fort Collins, Colorado.
[3] Stephen Smith is chairman and vice president of Aqua Engineering, Inc. in Fort Collins, Colorado.

INTRODUCTION

The case study presented is based on work we conducted for the New Opportunity Ditch Company. This ditch company was approached by a neighboring power company wanting to enter into an interruptible supply contract whereby the ditch company would interrupt irrigation supply to provide water for the operational of a coal-fired power plant.

As the ditch company considered this contract they realized there were many unknowns and risks they could not quantify and therefore could not appropriately weigh. The ditch company asked us to quantify the level risk they would experience if they were to enter into a contract with the power company.

Because the terms and conditions of this contract are currently under negotiation, we have used fictitious names in this manuscript for both the ditch and power companies.

Description of Contracting Entities

The New Opportunity Ditch Company. The New Opportunity Ditch Company owns both direct flow water rights from the South Platte River and storage water rights in the New Opportunity Reservoir, which are used to irrigate approximately 10,000 acres.

Many shareholders in the ditch company also supplement company-owned water supplies with wells that pump alluvial ground water. These ground water wells are tributary to the South Platte and as such impact or deplete water supply in the river when pumped. To remedy these impacts, tributary wells are required to operate within a state and water court approved augmentation plan.[4] The New Opportunity Ditch Company manages the augmentation plan for shareholders that use ground water wells.

To augment river depletions caused by ground water wells, the New Opportunity Ditch Company places junior water rights they own into off-channel recharge ponds when those water rights are in priority. The ditch company operates and

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[4] An augmentation plan provides a mechanism for junior water rights (e.g. ground water wells) to use water supplies out-of-priority in a way that protects senior water rights from the depletions caused by the junior pumping. Typically this will involve storing junior water when in priority and releasing that water when a call comes on; purchasing stored waters from other entities to release when a river call comes on; or purchasing senior irrigation water rights and changing the use of those rights to off-set the new users injury to the stream. (http://water.state.co.us/wateradmin/terms.asp#Augmentation%20plan:).

manages over 100 of these recharge ponds, most of which are located more than three miles from the South Platte River.

Water placed into these ponds seeps to the alluvial aquifer and travels towards the South Platte River. The aquifer attenuates these recharge events so that a steady stream of credits is generated at the South Platte River. One recharge event may provide a steady state of return each day for a period of several years or decades depending on its distance from the river and the aquifer properties.

The recharge credits generated by these ponds are used to offset the depletions at the river caused by ground water pumping. Based on the number of credits in any given year, the ditch company will issue a well pumping allocation to ground water users so as to best match ground water pumping to available recharge credits. New Opportunity's credits at the South Platte River typically exceed actual depletion caused by ground water wells.

The Watt Power Company. The Watt Power Company operates a coal-fired power plant on the South Platte River a few miles downstream of the New Opportunity Ditch service area. Like most coal-fired power plants, the Watt power plant requires a firm year-round water supply to cool operating equipment. The Watt Power Company approached the New Opportunity Ditch Company about entering into a contract that would supply their coal-fired power plant with between 3,000 and 5,000 acre-feet of water per year for the next 30 years.

The opportunity to enter into this type of contract is desirable to the New Opportunity Ditch because at many times of the year their recharge projects generate extra water or credits at the South Platte River. These credits could be used directly from the river by the power company to meet their needs. A contract to supply this excess water to the power company would provide for financial compensation that may not have otherwise been available.

Entering into this type of contract is also risky for the New Opportunity Ditch Company. At times, the ditch company may not have enough recharge credit at the river to meet the power company's needs. If the ditch company is unable to meet the terms of the contract using its recharge credits, they would have to guarantee delivery either by reducing their own augmentation needs (reduce ground water pumping) or, in a worst case, by using New Opportunity's senior storage water rights.

Monte Carlo Methodology

Applicability of Methodology. We determined that Monte Carlo simulations would best address the questions and concerns of the ditch company in this study. The Monte Carlo methodology presents results for a particular scenario in terms of a full range of risks. More commonly used methods provide limited answers to a particular scenario in terms of fixed assumptions like average or worst-case.

By using Monte Carlo simulations, we were able to decisively address the following questions posed by the New Opportunity Ditch Company:

- How likely is it that the ditch company recharge project will generate excess credits at the river to meet Watt Power's needs?
- How likely is it the ditch company will have to reduce their pumping allocation to well owners to meet the contract obligations?
- How likely is it that the ditch company will have to release water from their reservoir to meet the contract obligations?
- How does this likelihood change if New Opportunity Ditch enters into a contract level of 3,000 acre-feet per year as opposed to 4,000 or 5,000 acre-feet per year?

<u>Methodology Concepts</u>. Monte Carlo simulations are "stochastic techniques – meaning they are based on the use of random numbers and probability statistics to investigate problems" (Woller, 1996). Simulations that randomly generate thousands of values for uncertain variables will reveal a range of outcomes, not just one outcome. The range of outcomes can be interpreted in terms of probability. In other words, which outcomes are most or least likely to occur.

In this study, the outcomes using Monte Carlo simulations can be interpreted and framed not as distinct numbers but instead in terms like:

- "recharge projects are sufficient to meet Watt Power's needs in four years out of ten," or
- "in three out of ten years, it will be necessary to reduce well pumping allocation by 0.5 acre-feet per acre of land," or
- "in two out ten years, it will be necessary to release water from the New Opportunity Reservoir to meet the contract obligation."

Results in this form are more meaningful than just simply stating the average or worst case scenario one can expect.

Decisioneering's Crystal Ball 7 software was used to run the Monte Carlo simulations in this study. This software is essentially an "add-on" to Microsoft's Excel spreadsheet program. Although the model cannot run without Crystal Ball, the spreadsheets can be opened and viewed with Microsoft Excel alone.

The New Opportunity model relies heavily on calculations that can be computed directly using Excel functions. Crystal Ball is added to these existing calculations in the form of what are called "assumptions" and "forecasts".

Excel cells that serve as a "variable" to a particular calculation can be made an "assumption" in Crystal Ball. An assumption is a set of data that are distributed in some manner like normal, uniform or lognormal distribution. An assumption basically defines a variable in Excel as a range of values instead of just one value. Using Crystal Ball, a calculation set up in Excel can be run thousands of times, all the while picking (at random) a number from the distribution to serve as the variable in the calculation.

Similarly, the results or answer cells in Excel can be designated as “forecast” cells using Crystal Ball. A forecast is used to display the probability of obtaining particular outcomes or results. The forecast essentially stores the results of the thousands of trials that are drawn from the “assumptions.” These outcomes can be interpreted in terms of risk or uncertainty.

EVALUATION OF INTERRUPTIBLE SUPPLY CONTRACT

Model Input

The general approach to the New Opportunity Ditch Company project was to determine **when** and in **what amount** water is likely to be available to the recharge ponds over the contract period since this is the preferred water source for fulfilling a contract obligation. This supply is preferred because credits are consistently generated at the South Platte River – credits not used by the ditch company for augmentation would otherwise be left in the river and not used.

These uncertain variables were the driving force behind our statistical model – they were the Crystal Ball “assumptions” or data distributions that allowed us to test thousands of possible outcomes. We then evaluated these outcomes relative to the three proposed contract levels (3,000 acre-feet, 4,000 acre-feet, and 5,000 acre-feet) so the New Opportunity Ditch could contemplate what level of risk they were willing to accept, if any at all.

Water Availability to Recharge Projects. The recharge ponds that contribute to New Opportunity’s pool of recharge credits are relatively new – the earliest were constructed in the mid- to late-1970’s. Construction has continued until the present, with additional sites yet to be constructed.

Reliable records of water delivery to the ponds are available starting in 1985 and have continued through the present. Using this short period of record as a study period for the purpose of projecting future water supplies for the next 30 years (30 years being the term of the proposed interruptible supply contract) would yield potentially misleading results. Furthermore, this period coincided with rather extreme weather patterns for northeastern Colorado. The 1980’s and 1990’s were years of relatively plentiful rainfall, snowpack and streamflow. These years were then followed by the intense drought of 2002 through 2004 and again in 2006.

Considering these limitations in the delivery record, we determined the most useful predictor of recharge water availability would be the historical river call records. These records have been maintained consistently by the State Engineer for over 75 years. These records indicate which water rights were "calling" for water on a daily basis and also which days all water users were satisfied ("free river"). It is during these historical "free river" periods that water would have likely been available to New Opportunity's recharge sites, most of which have relatively junior water rights.

For example, Figure 1 shows the distribution of free river days in the month of July for the 75-year call record. This distribution shows that the most likely outcome in July is to have no days of free river (close to 50% of the time the number of free river days equals zero).

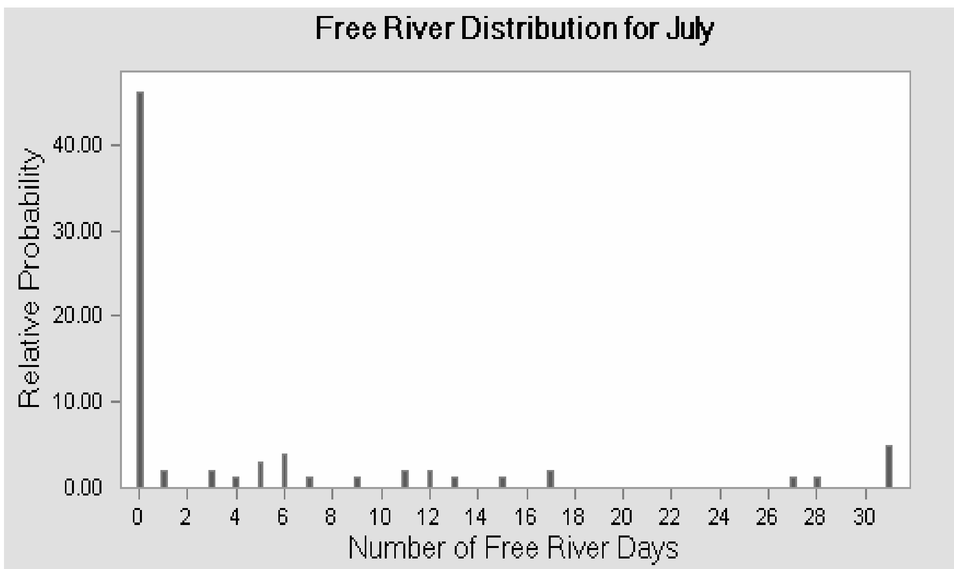

Figure 1. Distribution of free river days for the month of July from historical river call data set. Nearly 50% of the time (relative probability on y-axis), the number of days in July the South Platte River is "free," is zero.

July is the peak water demand period on the South Platte River because that is when irrigated agriculture uses the most water. It is therefore reasonable to expect that free river conditions are not as likely to occur during this month as river calls. This information helped us to understand the extent to which free water would have been available to New Opportunity's recharge projects. For example, over the next 30 years, New Opportunity Ditch might expect only half of the month of July to be free river and thus have water available to recharge projects.

Each month of the historical call record was modeled as an "assumption" in Crystal Ball. In essence, we put 75 years worth of "free river" periods into a hat and drew them at random to form 30-year sequences of recharge opportunities (or free river periods) the ditch company can likely expect in the future.

Quantity of Water Available to Recharge Projects. Once we determined **when** water would be available to the recharge ponds in the future, the next step was to model the **amount** of water available for delivery to recharge structures.

Rather than making uninformed guesses about the amount of water that would have been available over the 75-year period of call record, we tabulated actual deliveries into the New Opportunity recharge areas since 1985 by month, and limited our simulation to these actual historical deliveries. In other words, we assumed that future recharge would be no more and no less intensive than the recharge that has occurred historically.

Multiplying the number of free river days and available flow gives the total quantity of recharge water available in a particular month. For example, Figure 2 shows the distribution of flow available to recharge projects for the month of November. As shown, flow availability in November has been highly variable; it has been as low as 7.5 cubic-feet per second and as high as 98.6 cubic-feet per second.

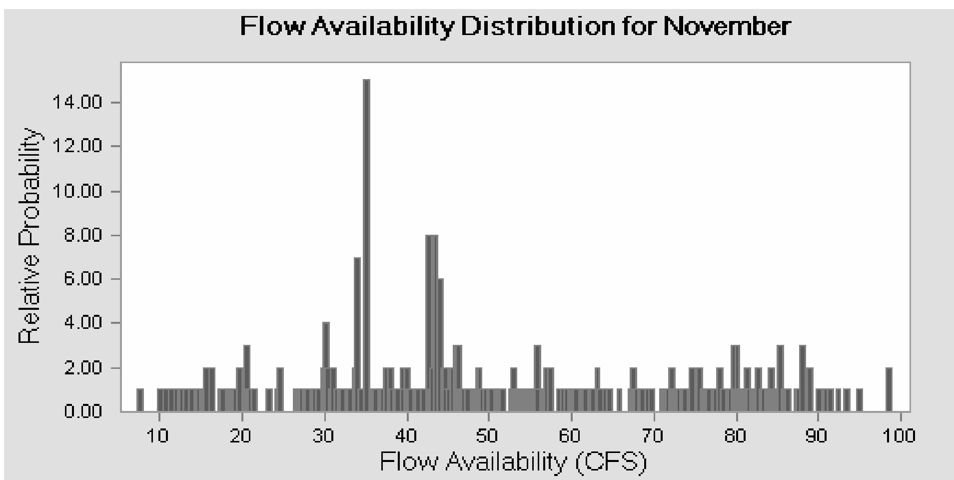

Figure 2. Distribution of daily flow available to recharge for November from actual delivery records to recharge ponds. Flow availability is highly variable.

Similar to the range of free river days, flow availability was also modeled as an "assumption" or range of variables in Crystal Ball.

Study Results

Assessing the Level of Risk. In assessing the risk associated with entering into a contract with the power company, the ditch company had to consider the tradeoff between financial compensation for entering into a contract and the amount of water that would likely be available to meet their irrigation needs. A higher contract amount may not be desirable if it will require the ditch company to regularly decrease the amount of ground water pumping allocated to well owners.

It may be even less desirable if the ditch company has to regularly forgo some portion of their senior reservoir water rights to meet contract obligations.

Figure 3 shows the results of the Crystal Ball model in the form of a "forecast" trend chart for the month of September assuming the ditch company enters into a contract to supply 3,000 acre-feet per year. September is presented because our model shows this to be the most critical month of the year for the ditch company because river credits from recharge are typically at their lowest level.

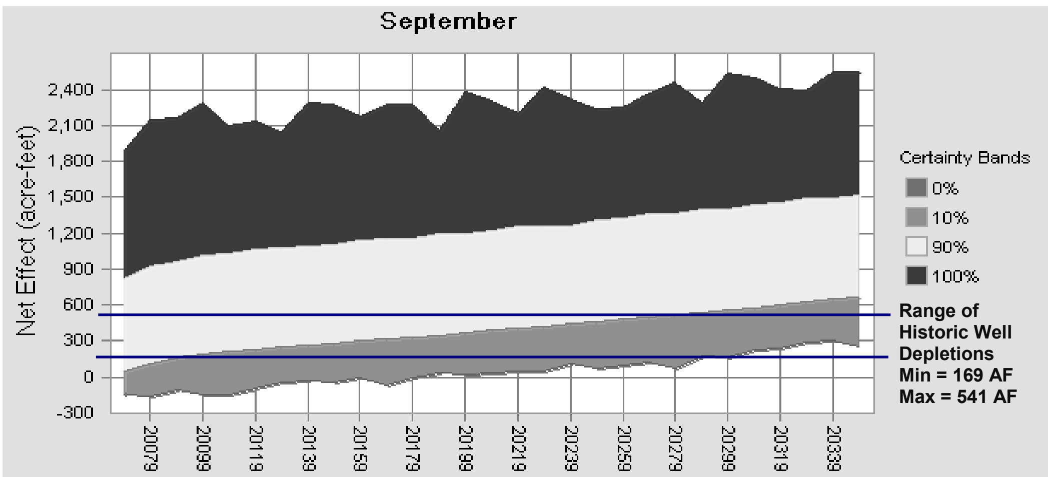

Figure 3. Forecast trend chart for 3,000 acre-feet contract level with Watt Power. Net effect represents the recharge credits available at the South Platte River after the contract obligation has been met.

The x-axis in Figure 3 represents the entire length of the contract period (30 years) or from year 2006 to year 2035[5]. The y-axis represents the net effect or the amount of recharge credits (in acre-feet) available at the South Platte River after contract needs are fulfilled. The net effect is the recharge water available to the ditch company for the issuance of pumping allocation for their augmentation plan. When net effect is positive, the ditch company has excess credits and may issue well owners full pumping allocation. When net effect is negative, the ditch company may have a deficit of recharge credits and may have to curtail pumping or in the worst case release water from their reservoir just to meet their obligation to the power company.

The color-differentiated certainty bands in Figure 3 display the distribution of outcomes or "forecasts" from the thousands of model runs in Crystal Ball. Each outcome falls within one of these bands. The bottom limit of the bands represents the lower limit for all outcomes. The top and bottom bands each represent the

[5] The x-axis label in Figure 3 includes the year and month. The year is stated first as four digits, the month is stated last as one digit. For September 2013, the label is 20139.

range of results that might be expected 10% of the time or 1 in 10 years for example. The bottom band represents the lower 10% of outcomes; the top band represents the upper 10% of outcomes. Combined, these two bands comprise a 20% frequency of outcome. The middle band displays the range of results that will be expected 80% of the time or 8 in 10 years.

At the 3,000 acre-feet contract level, no trial runs in the model produced a negative "net effect" after the year 2018. In other words, until the year 2018 (where bottom limit line moves above zero on the y-axis), the ditch company is at some level of risk of having a negative net effect at the river (i.e. they will have not generated enough recharge credits to meet their contract obligation with the power company). This risk is small at 10% or less until 2018.

Figure 3 also shows the range of historic ground water depletion from pumping that is expected during the month of September by New Opportunity well owners (between 169 acre-feet and 541 acre-feet). The certainty of having to reduce well depletions below the minimum historic pumping level exceeds 10% until year 2008 (where minimum pumping line intersects lower and middle certainty bands).

Figure 4 shows the forecast trend chart for a 4,000 acre-feet contract level. At this contract level, the ditch company is at a 10% risk of having a net negative effect at the river until the year 2026 (8 years longer than the 3,000 acre-feet contract level). The chance of having to reduce well depletions below the minimum historic level exceeds 20% until 2008, which is also greater than the 3,000 acre-feet contract level.

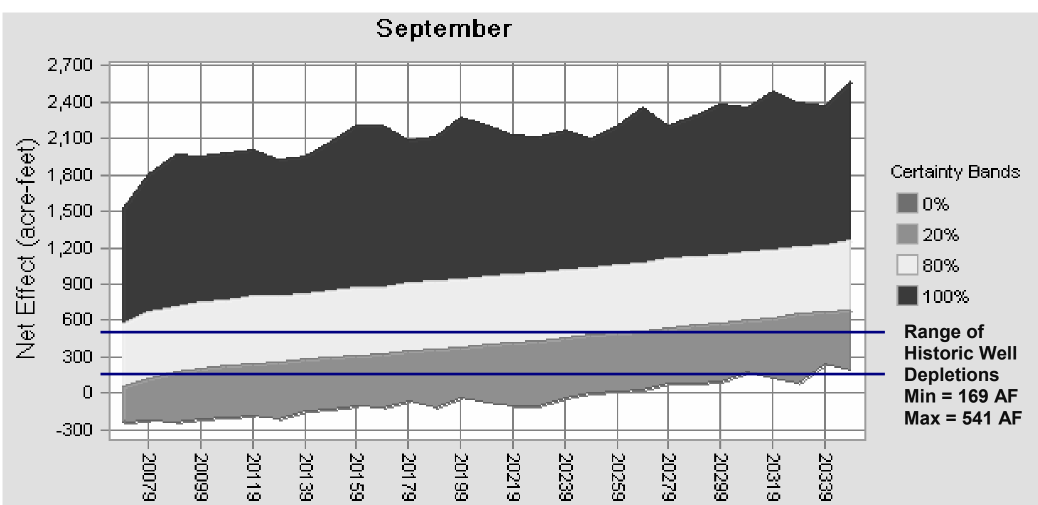

Figure 4. Forecast trend chart for 4,000 acre-feet contract level with Watt Power. Net effect represents the recharge credits available at the South Platte River after the contract obligation has been met.

Figure 5 shows the forecast trend chart for a 5,000 acre-feet contract level. At this contract level, the ditch company is at a 10% risk of having a net negative effect at the river until the year 2029 (only 3 years longer than the 4,000 acre-feet contract level). The chance of having to reduce well depletions below the minimum historic level exceeds 40% until 2007.

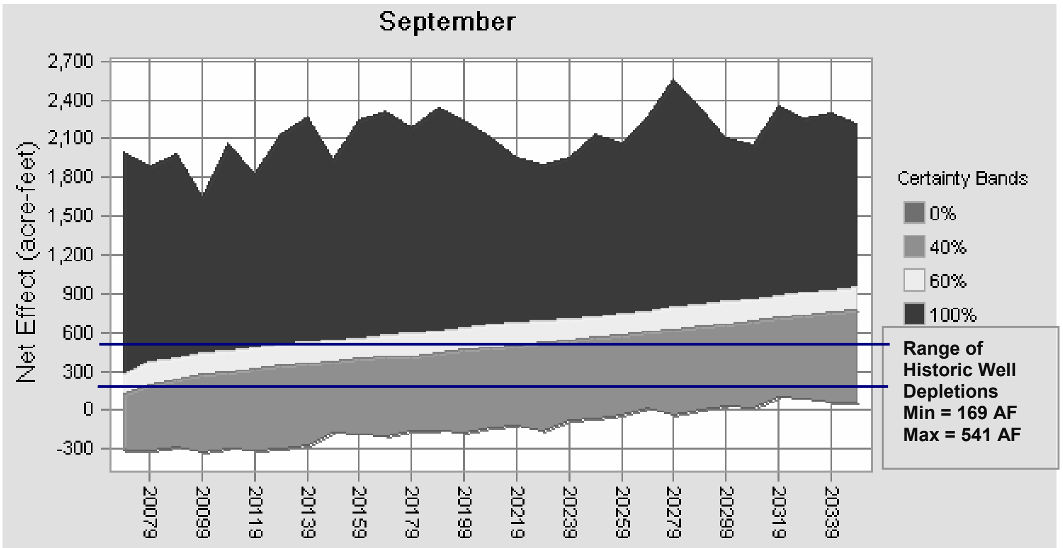

Figure 5. Forecast trend chart for 5,000 acre-feet contract level with Watt Power. Net effect represents the recharge credits available at the South Platte River after the contract obligation has been met.

In conclusion, the risk of having to release water from the New Opportunity Reservoir to meet contract obligations, at all contract levels, is less than 10% (likely to occur less than 1 in 10 years). At all contract levels, this risk goes to zero after some period of time – the higher the contract amount, the longer the period of risk.

Risk abates over the length of the study period as net effect or recharge credits increase. Because recharge ponds are located several miles from the river and because travel time is slow in the aquifer between the ponds and the river, many past recharge events have yet to accrue the river. Over the length of the contract term, New Opportunity expects a steady increase in these credits.

The risk of having to curtail ground water pumping allocation is highly variable between the three contract levels for the first several years of the contract. The risk of curtailment is four times greater at the 5,000 acre-feet contract level than the 3,000 acre-feet contract level.

SUMMARY

Risk was quantified using Monte Carlo simulations in Decisioneering's Crystal Ball Model. Using this model, we were able to substitute a full range of possibilities and test thousands of possible scenarios to determine which outcomes would be most likely for a proposed interruptible supply contract between a ditch company and power company. The intent was to provide risk levels to the ditch company so they could determine if and to what degree they wanted to interrupt their normal irrigation water supply to provide for the needs of the power company.

The results of this analysis are not as important as the methodology that was used and demonstrated in this manuscript. This methodology is not often used to evaluate risk in a water supply contract scenario. The intent of this paper was to demonstrate the applicability of this methodology for a multitude of applications and questions regarding risk and uncertainty.

REFERENCES

Colorado Division of Water Resources. http://water.state.co.us/wateradmin/terms.asp#Augmentation%20plan:

Decisioneering. Crystal Ball Version 7.1.2. Denver, Colorado. www.crystalball.com

Woller, J. (1996). The Basics of Monte Carlo Simulations. University of Nebraska-Lincoln. http://www.chem.unl.edu/zeng/joy/mclab/mcintro.html

AGRICULTURAL MANAGEMENT PRACTICES FOR PHOSPHORUS REDUCTION IN THE SALTON SEA WATERSHED

Khaled M. Bali[1]
Juan N. Guerrero[2]
Dan H. Putnam[3]

ABSTRACT

Nutrients, sediment and silt in drainage waters have been identified as the leading cause for water quality impairments in rivers and waterbodies in the State. In the Salton Sea Watershed in Southern California, more than 2.8 million acre-feet of Colorado River water are used every year to irrigate more than 500,000 acres of lands in the Imperial Valley. Approximately one-third of applied irrigation water leaves irrigated field as surface runoff and subsurface drainage. Surface and subsurface drainage water enters the Salton Sea, which has been serving as a drainage sink for the Imperial and Coachella Valleys since its formation in 1905. The Salton Sea continues to exist because of the drainage water from agriculture in Imperial and Coachella Valleys as well as flow of agricultural drainage and untreated and partially treated sewage from the Mexicali Valley. As the largest inland body of water in California, the Salton Sea provides significant habitat for fish and wildlife. Rising salinity, sediment, nutrients, and other pollutions threaten these habitats. Excessive loads of nutrients (mainly phosphorus and nitrogen) in Imperial Valley drains and rivers have contributed to the eutrophic conditions in the Salton Sea that impair the designated beneficial uses of the Sea.

Alfalfa is the principal crop in the Imperial Valley. Approximately 1 million ac-ft of water are used every year to irrigate 150,000 acres of alfalfa. Approximately 20 million pounds of phosphorus may be used annually to fertilize alfalfa in the Imperial Valley. In this study, we implemented four standard and improved irrigation and fertigation management practices on alfalfa fields to reduce the load and concentration of phosphorus and sediment in drainage waters. We evaluated the impact of each management measure on the load and concentration of phosphorus and sediment in drainage water. The most cost-effective measure was irrigation water management- determining and controlling the rate, amount, and timing of irrigation water applied. Reducing the amount of surface runoff after the

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[1]Irrigation/Water Management Advisor, University of California Desert Research & Extension Center, 1050 E. Holton Rd. Holtville, CA 92250. E-mail: kmbali@ucdavis.edu, Tel; 760-352-9474, Fax; 760-352-0846
[2]Livestock Advisor, University of California Desert Research & Extension Center, 1050 E. Holton Rd. Holtville, CA 92250.
[3]Extension Agronomist, University of California, Department of Plant Sciences, One Shields Avenue, 117 Hunt Hall, Davis, CA 95616.

application of P fertilizer is a key factor in reducing the load of P in drainage waters. The loads of P in runoff waters were reduced by as much as 75% compared to normal irrigation and fertigation practices.

INTRODUCTION

In California and elsewhere, how much of a pollutant a waterbody can tolerate on a daily basis is determined by setting a Total Maximum Daily Load (TMDL). A TMDL for agricultural drainage is defined as the load allocations for non-point source of pollution and natural background pollution, plus a margin of safety such that the capacity of the waterbody to assimilate pollutant loadings without violating water quality standards is not exceeded. A TMDL can be expressed in terms of either mass per time, toxicity, concentration, a specific chemical or other appropriate measures.

To comply with TMDLs and mitigate the impacts of agriculture drainage waters on other uses, irrigators and farm managers have to be more attentive to the quality of the water applied and the quality of drainage waters leaving their fields, as they must adjust their irrigation practices to ensure compliance with the regulatory standards. The presence of suspended sediment, phosphorus (P) 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.

Approximately 30% of applied drainage water in the Salton Sea watershed in southern California ends up as drainage water. Reducing the load and/or the concentration of suspended sediment in runoff has numerous benefits including reducing the amount of water applied and the load of other regulated contaminants such as pesticides and phosphorus that are attached to eroded soil particles. In this paper, we summarize our experience in using irrigation and fertigation management practices to reduce the load of phosphorus in runoff water from Irrigated fields in the Imperial Valley.

PHOSPHORUS LOAD IN RUNOFF WATERS

Surface irrigation, by mainly of furrows or border checks, is the primary method for irrigation in the Valley, and is used on more than 90% of the cropped area. Drip irrigation is used on less than 5% of the cropped area and mostly on vegetable crops. Sprinkler irrigation is mostly used to germinate some crops, but growers switch to surface methods once the crop is established.

The average concentration of suspended sediment in Imperial Valley drains and rivers is approximately 350-400 mg/L. Based on the average agricultural drainage discharge of 2.0 ac-ft per acre/year, this figure represents a net loss of approximately 1 ton of soil (in form of sediment) per acre per year. The average sediment load to drains and rivers in the Valley is in excess of 500,000 tons per year. In addition to the loss of productive topsoil, sediment and eroded soil particles contain considerable amounts of P attached to soil particles that eventually end up in the Salton Sea. The average concentration of soluble P in drainage water is approximately 0.5-1.0 mg/L (eutrophication, a major problem in the Salton Sea, can occur at concentrations as low as 0.02 mg/L). The average load of P in drainage water in form of P_2O_5 is approximately 5-10 lbs/acre (6-11 kg/ha) per year, with an average annual load of approximately 2.5 million lb (1.14 million kg) of P that end up in the Salton Sea every year.

Approximately 22 million lb (10 million kg) of phosphorus (in the form of P_2O_5) is used annually to fertilize the alfalfa crop (Meister et al., 2004), and this amount accounts for almost 50% of the total phosphorus applied to crops in the Valley. Phosphorus is applied once or twice per year as water-run phosphorus during the growing season with subsequent yearly applications in the springtime, or applied at a higher rate prior to planting to meet alfalfa demand for the entire growing season (approximately 3 years). The estimated phosphorus load in surface runoff waters is approximately 10-15% of total applied phosphorus. In addition, phosphorus may move directly to surface waters via sediments carried in the surface runoff, and via cracks in the soil to subsurface drains.

METHODOLOGY

A commercial alfalfa field in the Imperial Valley, CA was selected to conduct the study. The field is approximately 80 acres and it was planted with alfalfa in October 2004. Seven best management techniques (BMTs) for P load reduction to the Salton Sea were implemented during the second year of the project (1st year normal practices, BMTs in 2nd and 3rd year). The field consists of 13 standard borders approximately two hundred (200) feet wide by approximately one thousand two hundred (1,200) feet long. Flumes were installed at the head end and at the tail end of the field. Soil samples were collected at 300 and 900 ft along each border (lands 1 through 12) prior to applications (Table 2). Hay samples were collected at 300 and 900 ft along each border prior to each cutting.

Alfalfa yields were determined from sample cuttings and from bales. We counted hay bales on each border, weighted selected bales (one bale from each border), and recorded bale moisture from bales in each border. From bale data, we also estimated hay yields. Runoff water samples from each land were collected and the concentration of P and other water quality constituents (Table 1) were determined.

Table 1. Analytical instruments and flow rate measurement methods and quality assurance objectives.

Parameter	Method	Units	Detection limit	Sensitivity	Precision	Accuracy
Water delivered	Trapezoidal flume	Cfs	0 to 25	0.5 cfs	±4%	±10%
Runoff water	Long-throated flume	Cfs	0 to 9	0.2 cfs	±5%	±10
PO_4	US-EPA 365.2 (Acid Persulfate Digestion)	Mg/L	0-3.5	0.01	±5%	±5%
Salinity	EC (Tanji, 1990)	dS/m	0-3.0	0.05	±2%	±5%
NO_3	Spectrum™ (Cadmium Reduction Method)	Mg/L	0-30.00	0.01	±5%	±10%
Turbidity/ standard method	US-EPA 180.1	NTU	0-1000	0.1	±2%	±5%
Turbidity/ OBS-3 Suspended solids and turbidity monitor	D & A Instrument Company	FTU Mg/L	0.02-2,000 0.1-5,000 (Mud, D_{50}=10um)		2.0% (nonlinearity) 2.0% (nonlinearity	

The following P agricultural BMTs were implemented on the field (Table 2):

1. Irrigation water management — determining and controlling the rate, amount, and timing of irrigation water applied.

2. Runoff reduction — reducing the amount of surface runoff, using a runoff reduction method developed by UCCE, in just a single irrigation per year when water-run P fertilizer is applied

3. Precision application rates/GIS utilization — applying precise amounts of P-fertilizer to the soil in specific parts of the fields according to the plant needs.

4. Proper fertilizer applications — selecting the proper time and method of fertilizer application (water-run P applications vs. broadcast-P applications) to reduce P losses through runoff and soil erosion.

5. Improved water-run P application practices — applying 100 pounds/acre (equivalent P_2O_5) of water-run phosphorous in a single irrigation.

6. Reduced broadcast-P application practices — applying 75 pounds/acre of broadcast phosphorous fertilizer (in the form of P_2O_5) to the first 75% of the border.

7. Filter strip — establishing a section of land in permanent vegetation, downslope of agricultural operations.

Water-run phosphorus or dry phosphorus was applied to selected land according to the schedule shown on Table 2.

Table 2. Phosphorus application rates and methods

South

P rates	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13 extra
October 2004 before planting	S	3* S	S	S	S	S	S	S	S	S	S	S	S
March 2006	S RR	Zero	Zero	Zero	Zero	Zero	S	S RR	S RR	S	Zero	Zero	S
April 2006	Zero	Zero	WR 100 %	WR 75%	WR 75%	WR 100%	Zero	Zero	Zero	Zero	WR 100%	WR 75%	Zero
												FS	FS

S: Standard rate: 200 lbs of 11-48-0 (broadcast), approximately 100 lbs of P_2O_5
WR: Water run-P (phosphoric acid) approximately 100 lbs of P_2O_5
100%: Water run-P applied during the irrigation time
75%: Water run-P applied during the first 75% of irrigation time
RR: Reduced runoff
FS: Filter strip in 2006/2007
PA: Precision application in 2007
Soil samples: surface-2”, 6”, 12”, 18”, 24”, 36”, 48”, and 60”.Samples collected from two locations (300 and 900 ft) along each border.

RESULTS AND DISCUSSION

Suspended solids concentration-Turbidity (C-T) relationship in runoff water

Preliminary data obtained during the first seven months of 2006 are discussed here. The concentrations of sediment (C) in runoff water were determined form turbidity (T) values using three C-T functions determined earlier in a previous study (Gao et al., 2005). Three possible C-T functions were tested by regression analysis (1) linear function, (2) threshold linear functions (i.e. two linear functions for data with NTU < 200 and NTU ≥ 200), and (3) power function. The regression results were compared with one another and the function with the best fit was selected.

For all turbidity measurements, the errors between the reading and the standard values were between 0.2% and 2.4% signifying that the turbidity values measured by the turbidity meter were reliable. The regression results based on the data and their corresponding relations are:

Linear function — $C = 0.876T + 29.2$ (1)

Threshold linear functions

$C = 1.162T + 18.5$ NTU < 200 (2a)

$C = 0.898T + 12.1$ NTU ≥ 200 (2b)

Power function — $C = 3.6T^{0.8}$ (3)

Although the linear function fitted the data well for high turbidity values, it over predicted *C* for *T* values less than 30 NTU. The two threshold linear functions agreed with the data well at high turbidity values but still over predicted *C* at low turbidity values. In addition, the two intercepts in the two types of linear functions indicated that as turbidity approached zero, *C* was 29.2 and 18.5 mg/L, respectively. This was contradicting to the value (i.e. zero) generated by pre-programmed formazin calibration. The power function fitted the data well at both low and high turbidity values. Validation of eq. (3) using the data collected in previous experiments indicated that the power function represented the best relationship between C and T. Therefore, we used eq. (3) to calculate the concentration of sediment in runoff water.

Sediment and phosphorus concentrations and loads in runoff waters

The average concentration of suspended sediment in runoff water for all irrigation and P application practices was lower than 120 mg/L (Table 3). That is well below the TMDL threshold rate of 200 mg/L. This indicates that any of the irrigation or fertigation practices has little impact on water quality.

Table 3. Average sediment concentration in runoff water (mg/L).

		P application type and irrigation practice			
Irrigation number after P application	Irrigation date	Standard P rate broadcast-standard irrigation (borders L7, L10, L13)	Standard P rate broadcast-reduced runoff (borders L1, L8, L9)	Standard P rate water-run- standard irrigation (borders L3,L6, L11)	75% of standard P rate- water-run- standard irrigation (borders L4, L5, L12)
Pre-application irrigation	3/21-23/2006	57	78	61	65
1st irrigation	4/27/2006	97	66	58	153
2nd irrigation	5/10/2006	69	63	66	64
3rd irrigation	5/29/2006	118	83	74	66
5th irrigation	6/26/2006	105	161	94	105
6th irrigation	7/11/2006	33	45	56	58

The average concentration of P for selected irrigation and fertigation practices are shown in Table 3.The concentration of P in runoff water prior to P application practices was in the range of 1.63 to 3.99 mg/L. The concentration of P in runoff water increased dramatically after all P application practices. The concentration of P in runoff water after dry P broadcast applications reached 118 mg/L (Table 4). However, the concentration of P in runoff water after the water-run applications was much higher than the concentration after the dry P broadcast applications (in excess of 218 mg/L). Applying P during the first 75% of irrigation time had no impact on P concentration in irrigation water. The average concentration of P in runoff water during the first six irrigations after P applications was the highest for the 75% water-run P application practice (46 mg/L). The standard broadcast-reduced runoff practice had the lowest average concentration of 18 mg/L. That is almost 50%lower than the water-run P application practices.

Table 4. Average phosphorus (PO_4) concentration in runoff water (mg/L).

		P application type and irrigation practice			
Irrigation number after P application	Irrigation date	Standard P rate broadcast-standard irrigation (borders L7, L10, L13)	Standard P rate broadcast-reduced runoff (borders L1, L8, L9)	Standard P rate water-run- standard irrigation (borders L3,L6, L11)	75% of standard P rate- water-run- standard irrigation (borders L4, L5, L12)
Pre-application irrigation	3/21-23/2006	3.99	3.76	1.77	1.63
1st irrigation	4/27/2006	117.93	77.41	192.30	218.44
2nd irrigation	5/10/2006	3.97	4.35	5.49	5.62
3rd irrigation	5/29/2006	2.32	3.85	2.68	2.94
5th irrigation	6/26/2006	1.32	4.49	2.79	3.22
6th irrigation	7/11/2006	0.71	1.51	1.42	1.24
Average (1st-6th)		25.25	18.32	40.94	46.29

The average load of P per irrigation during the first six irrigations after P applications is less than 1 lb/acre per irrigation in the standard broadcast-reduced runoff irrigation (Table 5). The load of P in runoff water for this treatment was almost 75% lower than any other P application or fertigation practice. Controlling the rate and the amount of applied water is the most effective way to reduce the concentration and load of P in runoff waters.

Table 5. Average phosphorus (PO_4) concentration and load in runoff water during the first six irrigation after P application*

P application type and irrigation practice	Average P concentration (mg/L) per irrigation	Average P load per irrigation (lb/acre)
Standard P rate broadcast-standard irrigation (borders L7, L10, L13)	25.25	4.37
Standard P rate broadcast-reduced runoff (borders L1, L8, L9)	18.32	0.93
Standard P rate water-run-standard irrigation (borders L3,L6, L11)	40.94	7.09
75% of standard P rate- water-run- standard irrigation (borders L4, L5, L12)	46.29	8.01

*Based on average application depth of 4.5 inches (11.4 cm) and runoff rates of 17% and 5% for standard irrigation and reduced runoff practices, respectively.

CONCLUSIONS

Irrigation management is a key factor in controlling the concentration and the load of P discharged from irrigation fields in the Imperial Valley. Reducing the rate of surface runoff during and after P application practices could reduce P load into surface waters by as much as 75% as compared to standard irrigation practices. Water-run application of P increased the concentration and load of P in runoff water.

REFERENCES

Davis-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.

Gao. P, G. Pasternack, K. M. Bali, and W. W. Wallender. 2005. Impact of Agricultural Practices on Soil Erosion
at the Field Scale in The Salton Sea Watershed. In the Proceedings of the Third International Conference on Irrigation and Drainage. Water District Management and Governance. USCID. pp:571-580.

Meister, H, K. M. Bali, E. T. Natwick, T. Turini, and J. N. Guerrero. 2004. Guidelines to production costs and practices for Imperial County-Field crops. UCCE_Imperial County Circular 104-F. http://ceimperial.ucdavis.edu.

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MANAGING ACROSS GROUNDWATER AND SURFACE WATER: AN AUSTRALIAN 'CONJUNCTIVE LICENCE' ILLUSTRATION OF ALLOCATION AND PLANNING ISSUES

Imogen Fullagar[1]
Dr. Catherine Allan[2]
Prof. Shahbaz Khan[3]

ABSTRACT

Conjunctive use of groundwater is a common irrigation response to limited surface water availability. In the late 1970s, under a 'one resource policy', the New South Wales (NSW) government of Australia began issuing a form of conjunctive licence to irrigators with access to both surface water and groundwater. These licences were intended to provide the licence owners with the water supply security offered by conjunctive use. Institutional separation of groundwater and surface water prevented accounting across the resources. As a result the licences contributed towards over-allocation of groundwater. Conjunctive licences were subsequently discontinued and separated into surface water and groundwater components in the late 1990s. This paper explores the NSW experience of conjunctive licences in light of Australia's recent national agreement to manage connected surface water and groundwater as one resource. The conclusion is that flow systems cannot be allocated as 'one resource' if managed through independent groundwater and surface water planning institutions. Some implications and options for allocation across local water resources with hydraulic connectivity are considered.

INTRODUCTION

Freshwater flow systems are commonly comprised of both groundwater and surface water (Winter *et al*, 1998). In such systems, development of surface water will impact groundwater over time, and vice versa. These impacts are of increasing interest as demand for freshwater and sustainable management grows. Related issues include irrigation-induced salinity and declines in environmental

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[1] Cooperative Research Centre for Irrigation Futures PhD candidate (Charles Sturt University). Postal address: c/o CSIRO Land and Water, GPO Box 1666, Canberra ACT 2601, Australia. Email: imogen.fullagar@csiro.au
[2] Environmental and Information Science Lecturer. Postal address: Charles Sturt University, PO Box 787, Albury NSW 2640, Australia. Email: callan@csu.edu.au
[3] Research Director (CSIRO) and Professor of Science and Technology (Charles Sturt University). Postal address: Charles Sturt University, Locked Bag 588, Wagga Wagga NSW 2678, Australia. Email: skhan@csu.edu.au

health. Utilisation of system function and system accounting are central themes to related discussion (Qureshi *et al* 2002, Blomquist *et al* 2004).

The Australian priority of water management has been driven by a climate characterised by highly variable rainfall. This status has seen Australia active in the investigation of groundwater-surface water interaction and management (Braaten and Gates, 2003; Khan *et al,* 2003; Fullagar 2004; Evans *et al* 2005).

In Australia, the seven State governments maintain independent constitutional authority for water legislation and management within their respective jurisdictional boundaries. These States are federated under a national Australian Government. While the Australian Government has no direct responsibility for water management, it has had a key role in coordinating agreement and delivery of national water agendas (Tisdell *et al*, 2002) – a role supported by international responsibilities and economic leverage allowed through the Commonwealth of Australia Constitution Act (1900).

The most recent of such agendas is the National Water Initiative (Council of Australian Governments (COAG) , 2004) which outlines national water industry objectives for the period 2004 to 2014. The National Water Initiative includes in its objective:

> *"recognition of the connectivity between surface and groundwater resources and connected systems managed as a single resource"*
> (pg 4; COAG, 2004).

This objective begs the question of how to allocate groundwater and surface water as a single resource within a connected system.

This paper outlines an unsuccessful attempt by the Australian state of NSW to allocate across groundwater and surface water via a form of conjunctive licence. This effort is analysed for institutional lessons of general relevance to water management.

THE NSW CONJUNCTIVE LICENCE CASE STUDY

<u>Data sources</u>

The NSW Department of Natural Resources is responsible for water licensing in NSW, however licensing is issued through regional centres. Departmental structure and records have been subject to two major restructures between 2002 and 2005. There is no known compilation of the history of NSW conjunctive licences. Information relating to the experience is therefore patchy and heavily dependent on corporate knowledge.

Information for this case study was sourced through discussion with departmental officers (see acknowledgements), and a review of records these officers maintained for personal reference.

Background

Prior to the 1980s, NSW allocated water in the form of perpetual irrigation licences on the basis of land area rather than by volume (Taylor *et al,* 2001). Under these arrangements, surface water and groundwater licences were issued on the basis of demand and distinguished by associated infrastructure works. Irrigation licences were predominantly surface water licences.

By the mid-1970s, over-allocation of surface water became increasingly evident as land was developed for irrigation and associated water rights realised (Haisman, 2005). Naturally high variability of surface water availability also limited security for irrigation development. However, developers had invested on the understanding that area based water rights could be realised. A call for resolution of the discrepancy between allocated surface water and available surface water began radiating from nodal regions, notably the Namoi and Lachlan Valleys to the north of the State. Both public and private sectors looked to groundwater as a potential solution.

Nature of conjunctive licences

NSW conjunctive licences were bore (groundwater) licences issued with a conjunctive condition. Under the conjunctive condition, the allocation of the licence was inversely dependent on seasonal surface water availability: the lower surface water availability, the more groundwater the licence would allow to be accessed. The conjunctive condition was accompanied by a scale factor which dictated the conversion scale through which groundwater allocation was calculated. This conversion ratio was originally 1:1, but adapted to try and account for local impacts such as declines in groundwater tables. (This paper focuses on the principles of the NSW conjunctive licence system and does not further consider the detail of these ratio changes).

Thus in areas where conjunctive licences were issued, two types of groundwater allocations existed:

1. standard groundwater licence (a fixed allocation as required by irrigators who were wholly groundwater dependent), and
2. conjunctive licences (for which allocation varied in response to annual surface water allocation).

Where and when conjunctive licences were issued

Conjunctive licences were first issued in the Lachlan in 1976. The practice was subsequently extended to the across the northern irrigation areas of Namoi, Gwydir, and Border Rivers. In 1979, the issuing of conjunctive licences was adopted under a 'one resource' policy which sought to realise the drought security potential offered by groundwater resources (Department of Land and Water Conservation, 1997).

In the mid-1980's, land area based water rights were converted to volumetric licences (Taylor *et al,* 2001). During this conversion, the conjunctive condition was applied as a matter of course to bore licences owned by landholders with surface water rights. This resulted in the issue of conjunctive licences being extended to areas including the Macquarie, Cudgegong Valley, Murrumbidgee, and the lower Murray. Records exist for 94 conjunctive licences in the lower Murray, and over 300 conjunctive licences are believed to have been issued in the Namoi Valley. The Namoi Valley is recognised as having had the greatest concentration of conjunctive licences. On this basis it is estimated the number of conjunctive licences issued across NSW was in the order of 1000.

Institutional issues and separation of conjunctive licences

NSW institutions treat groundwater and surface water as conceptually independent resources. This practice reflects the dominance of surface water demand in water development, and is a logical extension of differences in aquifer and surface storage attributes and infrastructure works required for access (Turral and Fullagar, 2006).

In accordance with the National Strategy for Ecologically Sustainable Development (COAG, 1992), NSW water management aims to:

1. maximise the economic return from available resources, and
2. (for renewable resources) define availability through sustainable limits.

NSW institutions have seen these objectives applied consistently but independently to surface water and groundwater. As result, surface water plans are therefore encouraged to fully account the development of a resource with highly variable availability, while groundwater plans are designed to fully account the development of a resource with stable availability.

Under conjunctive licences, surface water allocation which was unmet in years of low rainfall (see Figure 1a) became groundwater allocation. This resulted in the variable allocation of groundwater – a resource with stable availability (see Figure 1b).

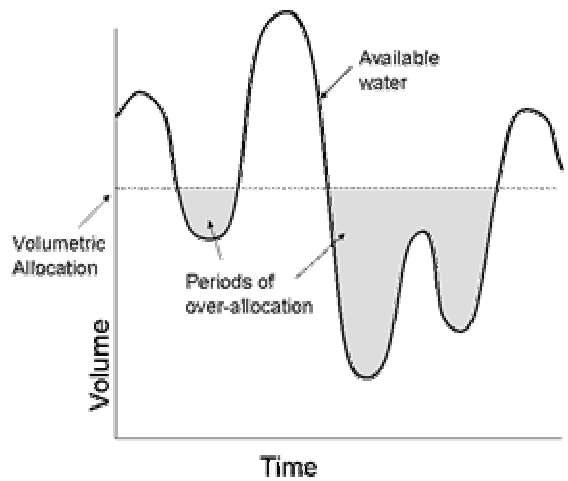

Figure 1a: Surface water allocation and availability

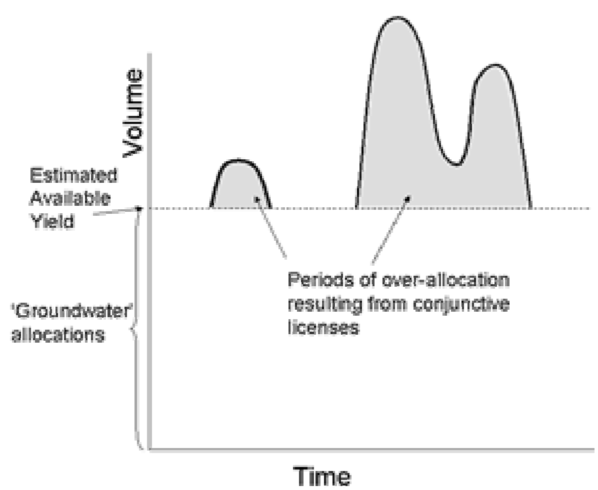

Figure 1b: Impact of surface water availability on groundwater demand under conjunctive licences

This variability could be accommodated by either setting groundwater allocation limits on the basis of a maximum estimate of conjunctive demand (Figure 2a), or accepting periodic over-allocation and under-allocation of groundwater (Figure 2b).

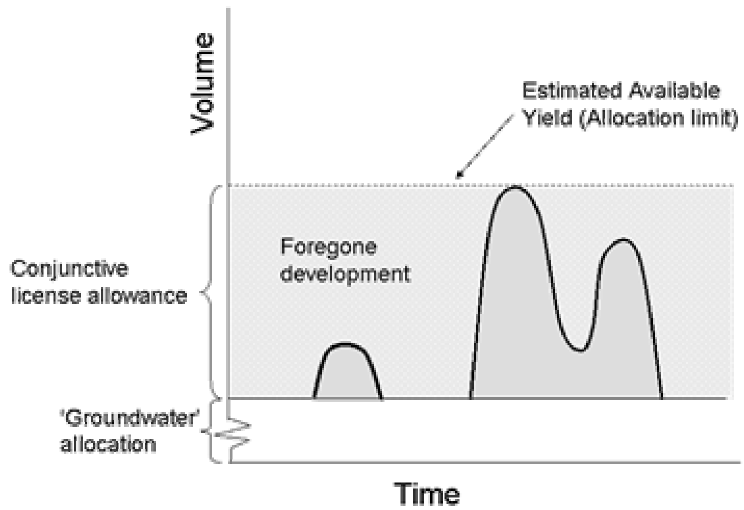

Figure 2a: Effect of allocating groundwater with full allowance for conjunctive demand

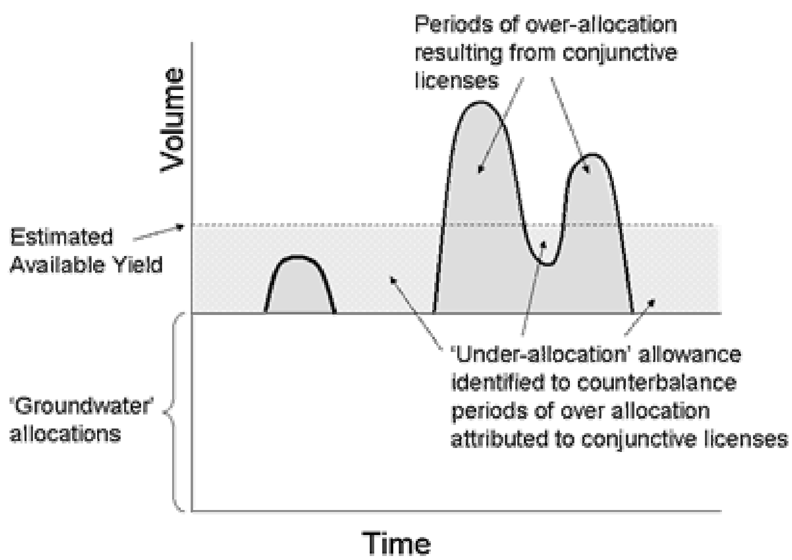

Figure 2b: Effect of allocating groundwater with partial allowance for conjunctive licences

The option illustrated in Figure 2a would result in underutilisation of available groundwater, which contradicted maximum economic return of groundwater. The option illustrated in Figure 2b contradicted sustainability policies by allowing for over-allocation (which would increase with any long term decline in surface water availability).

In both options, the protection of conjunctive users was absorbed by groundwater-dependent irrigation through either unrealised development (Figure 2a) or lost resource security (Figure 2b).

In recognition of these inconsistencies, the NSW government decided to discontinue conjunctive licences in the late 1990s (Gates and O'Keefe, 1999). Most conjunctive licences have since been separated into independent groundwater and surface water components.

Subsequent institutional developments

The decision to separate conjunctive licences into groundwater and surface water components reinforced the practice of managing groundwater and surface water resources as institutionally independent entities. This practice has been cemented through progressive enactment of the NSW Water Act 2000. The 'water sharing plans' underpinning this Act are typically distinguished as 'regulated water sharing plans', 'unregulated water sharing plans', or 'groundwater sharing plans' (see Figure 3). Where this has not been the case (eg Department of Infrastructure Planning and Natural Resources, 2003) groundwater and surface water allocation limits are independently specified within the plan.

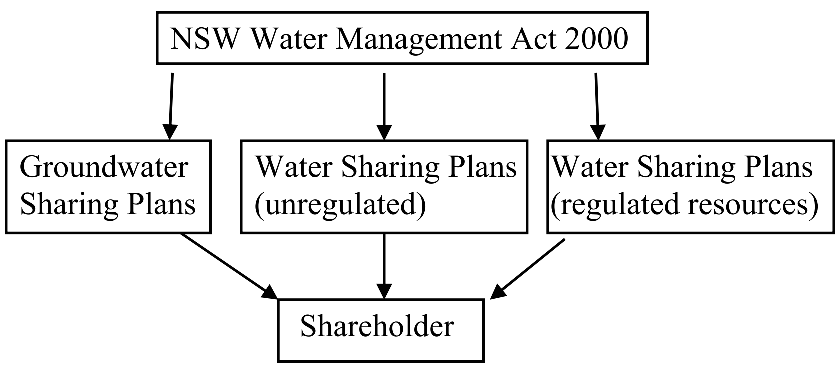

Figure 3: Water Management under the NSW Water Management Act 2000

The NSW Water Act 2000 requires the conversion of water licences from volumes to shares of the water resource specified within a water sharing plan. Within the share structure, all allocations covered by surface water plans are shares in a surface water resource, and all allocations covered by groundwater sharing plans are shares in a groundwater resource.

Table 1 uses the example of water sharing plans applicable to Coleambally (a NSW irrigation area within the Murrumbidgee catchment) to illustrate the discrepancies parallel but independent groundwater and surface water institutions create between local groundwater and surface water shares. Most notably: volumetric conversion of groundwater and surface water shares occurs through independent availability announcements. A local groundwater share therefore does not have the same volumetric value as a local surface water share. Water management opportunities for the different resources are further separated by independent carry-over and trade opportunities.

Table 1. Institutions for surface water and groundwater in Coleambally

	Surface water	Groundwater
Act	*NSW Water Management Act 2000*	
Relevant Plan	*Water Sharing Plan for the Murrumbidgee Regulated River Water Supply* (Department of Infrastructure Planning and Natural Resources 2003)	*Water Sharing Plan for the Lower Murrumbidgee Groundwater Sources* (Department of Infrastructure Planning and Natural Resources, deferred)
Entitlements secured as	Shares of resource defined by plan	
Shares converted to volume by	Allocation	
Availability announced	Monthly (fortnightly in peak season) with annual prediction.	Annually. An estimation of annual sustainable yield is provided and forms the basis of the 10 yr plan.
Annual carry-over capacity	15% of allocation	50% of allocation
Trade potential	• Within water resource defined by plan • Between NSW water resources on a common river system • Between States which the river system crosses	• Within water resource defined by plan (may be restricted to local impact 'zones') • It is possible sell out of an over-allocated plan, but this requires creation of a buying market in developing areas

These arrangements make it difficult to equate local groundwater shares with local surface water shares, even where these property rights apply to hydraulically interdependent resources. This institutional context is a challenge for the management of connected systems as a single resource (Objective 23(x), COAG, 2004).

DISCUSSION

The NSW Water Sharing Plans consider and make provisions for environmental needs. Groundwater sharing plans are required to make environmental allocations as necessary to protect identified groundwater dependent ecosystems, including dependent surface flows. Surface water sharing plans are required to consider in-stream and terrestrial environmental needs. However within these plans, aquifer recharge is generally not considered or managed as a stream dependency, but as a component of transmission or unaccounted 'losses'. System water accounts by Khan *et al* (2003) clearly demonstrate the importance of water exchanged between surface and underground components of a flow system, and water truly 'lost' from that system (eg by evaporation).

The 10 year timeframe of the NSW Water Sharing Plans seeks to strike a balance between the competing objectives of water property right security (ie through clear articulation of priority commitments such as the environment) and adaptive management. Independent plans means that within the 10 year span of these plans, groundwater and surface water availability are not designed to be responsive, even where these resources are hydraulically connected. Mechanisms for response under the NSW structure are by changing annual groundwater allocation, changing fortnightly surface water allocation, or changing long term allocations via the water sharing plans.

These options have capacity to respond to changes in water availability which can be attributed to development of adjacent resources, however they do not provide for proactive management of connectivity as might be allowed by active management of aquifer storage. This inflexibility could prevent the full potential productivity of water resources from being realised where it was feasible to over-draw and refill aquifer stores through conjunctive management of local groundwater and surface water systems.

Practical options allowed within the structure of water sharing plans include limiting the distance between bores and streams (Department of Land and Water Conservation, 2002). Evans, Dudding and Holland (2005) have further developed this concept, proposing groundwater allocation be accounted as a function of surface water through zones based on geology, distance from surface water flows, temporal displacement of impact, and managed temporal access to groundwater. This option protects the integrity of existing groundwater and surface water allocation institutions, but involves costs of groundwater access and trade constraints within the defined zones.

The NSW conjunctive licensing experience suggests that the allocation of groundwater and surface water as a single resource is dependent on a more fundamental reconciliation of groundwater and surface water planning and accounting.

Management across groundwater and surface water has been observed to be simple in concept, but difficult in practice (Qureshi *et al,* 2002). The NSW conjunctive licence experience illustrates constraints may be institutional as well as hydraulic where independent groundwater and surface water allocation regimes have been adopted.

Allocation of common shares across local groundwater and surface water components is not an easy option. The development of management arrangements requires clear definition of clear resource boundaries (Ostrom, 1992). Without such boundaries, it is difficult to separate management impacts from third party impacts. Boundary definition is a nontrivial task for groundwater-surface water resources, because groundwater boundaries can transcend topographical catchments (typically used to bound surface water resources).

Furthermore, surface water tends to be the preferred resource where it is available. To protect environmental allocations, a 'one resource' share allocation system would therefore need to limit the realisation of shares as surface water. A similar framework for the geographic distribution of groundwater accessions would be required to prevent foci of over-draw.

A common share approach may also limit capacity to effectively address issues specific to groundwater or surface water. These could include issues of water quality, mobilisation of soil salts, maintenance of infrastructure standards, and management for specific environmental objectives.

Finally, under a common share approach, all local water shares would have similar relevance to the water trading market. Existing water trading markets are established on flow attributes and regulation of river or aquifer systems. Consistency of local water shares would not make this distinction, and therefore be inconsistent with regional water markets. This could significantly compromise the economic opportunities which exist where local water shares can be traded on a larger market.

CONCLUSION

The key conclusion to be drawn from the NSW conjunctive licence experience is that flow systems cannot be allocated as 'one resource' if managed through independent groundwater and surface water planning institutions. The experience also suggests that local allocation mechanisms must be consistent with broader scale allocation mechanisms if trading opportunities are to be retained.

Concern for future river flows is currently driving groundwater policy agendas in Australia. Australian governments are therefore increasingly looking to integrate groundwater and surface water management. All management options must address the reality that water is a limited resource. The challenge is full evaluation and accounting of the benefits and costs of different options, while accounting for differences between sites and communities. These benefits and costs may be resource specific, but they may also relate to costs and benefits of property right management options such as trade. In developing an appropriate range of options, Australia is advantaged by common political, social and hydraulic incentives for improving management across groundwater and surface water.

ACKNOWLEDGEMENTS

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REFERENCES

Blomquist W, Schlager E, Heikkila T (2004). *Common Water, Diverging Streams.* Resources for the Future, Washington DC.

Braaten R and Gates G (2003) 'Groundwater-surface water interaction in inland New South Wales: a scoping study', *Water Science Technology*, vol 48(7), pp. 215-24

Council of Australian Governments (1992) National Strategy for Ecologically Sustainable Development. Available online at www.deh.gov.au/esd/national/nsesd/index.html

Council of Australian Governments (2004) Intergovernment Agreement on a National Water Initiative. Available online as "NWI Agreement" at www.nwc.gov.au/NWI

Department of Infrastructure Planning and Natural Resources (2003) Water Sharing Plan for the Dorrigo Plateau Surface Water Source and the Dorrigo Basalt Groundwater Source. NSW Government, Sydney. Available online at: www.dnr.nsw.gov.au/water/sharing

Department of Infrastructure Planning and Natural Resources (2003) Water Sharing Plan for the Murrumbidgee Regulated River Water Supply. NSW Government, Sydney. Available online at: www.dnr.nsw.gov.au/water/sharing

Department of Infrastructure Planning and Natural Resources (deferred) Water Sharing Plan for the Lower Murrumbidgee Groundwater Sources. NSW Government Sydney. Available online at: www.dnr.nsw.gov.au/water/sharing

Department of Land and Water Conservation (1997) Groundwater Management Area 011 (Upper Lachlan) – Groundwater Management Policy 1997 – 2002. NSW Government, Sydney.

Department of Land and Water Conservation (2002) The NSW State Groundwater Dependent Ecosystems Policy. NSW Government, Sydney.

Evans R, Dudding M, Holland G (2005) River-groundwater interaction, a practical management approach. Paper presented at 29th Hydrology and Water Resources Symposium, 21-23 February 2005, Engineers Australia, Canberra.

Fullagar, I (2004) Rivers & aquifers: towards conjunctive water management (workshop proceedings). Bureau of Rural Sciences, Canberra. Available as free download by following Bureau of Rural Science link on www.daff.gov.au/content/publications.cfm

Gates G and O'Keefe V (1999) Sustainable groundwater management in NSW, Australia. In proceedings of the Murray-Darling Basin Groundwater Workshop, Griffith NSW, 14-16 September, pp 35-41.

Haisman B (2005) Impacts of water rights reform in Australia. Chapter 5 in: Bruns BR, Ringler C and Meinzen-Dick R (Eds) Water Rights Reform: Lessons for Institutional Design. International Fool Policy Research Institute, Washington DC

Khan S., Beddek R, Blackwell J, Carroll J, Tariq R and Paydar Z. (2003) Whole of Catchment Water and Salt Balance to Identify Potential Water Saving Options in the Murrumbidgee Catchment. Consultancy Report for Pratt Water Initiative in the Murrumbidgee catchment.

Ostrom E (1992). *Crafting institutions for self-governing irrigation systems*. San Francisco: Institution of Contemporary Studies.

Qureshi AS, Bhatti A, Jehangir WA (2002) Managing Surface and Groundwater Resources: Proceedings of the International Workshop on Conjunctive Water Management for Sustainable Irrigated Agriculture in South Asia. Lahore: International Water Management Institute.

Taylor P, McGlynn T, and Martin W (2001) The influence of privatisation on irrigation water rights in NSW. Paper presented at the Regional Conference of the International Association for the Study of Common Property. Brisbane, Australia, September 2001.

Tisdell J, Ward J, and Grudzinski T (2002) The development of water reform in Australia. Technical Report 02/05. Cooperative Research Centre for Catchment Hydrology. Monash University, Melbourne.

Turral, H and Fullagar I (2006). Institutional directions in groundwater management in Australia. Chapter 15 in *The Agricultural Groundwater Revolution: Opportunities and Threats to Development.* CABI Publishing (in press)

Winter TC, Harvey JW, Franke OL and Alley WM (1998) 'Groundwater and surface water: a single resource'. Circular 1139, US Geological Survey, Denver Colorado

DECENTRALIZED FLOW MONITORING IN EGYPT

Dr. Ragab Abdel Azim[1]
Eric Viala[2]

ABSTRACT

The equitable and accountable allocation of water resources is a critical step towards water use efficiency. This is especially true in Egypt where multiple and growing demands are competing for a limited water supply (Egypt's share of the Lake Nasser reservoir, behind the High Aswan Dam). The Egyptian per capita annual water share has in recent years decreased below the 1000 m^3 threshold.

Water distribution in Egypt strives to maintain optimal water levels in the main canals, high enough to ensure gravity supply of secondary and tertiary canals, while preventing bank overflow. The monitoring of flows is limited to main canals and critical locations at the national level to optimize water distribution.

The MWRI has recently taken steps to simplify its structure by establishing Integrated Water Management Districts (IWMDs). These IWMDs are empowered with most water management responsibilities, notably monitoring water resources. The USAID-funded LIFE-IWRM Project has supported this effort through the procurement of equipment and the training of IWMD staff.

Each of the newly established 27 IWMDs has now defined a flow monitoring network which includes the locations of main inflow and outflow structures. Discharge measurements are being carried out twice a month in each of these locations, while water levels and gate openings are recorded daily. All of these inflow and outflow structures have recently been calibrated, thus allowing IWMD managers to know the daily volumes of water being supplied to their district.

This process of decentralized flow monitoring is a first step on the road from water distribution to water management. Reliable information on actual supplied volumes is essential and can then be compared to actual demands to improve water use efficiency.

INTRODUCTION

Egypt's water supply relies almost exclusively on the Nile through the huge reservoir behind the High Aswan Dam: Lake Nasser. Out of an annual inflow of

[1] Senior Director of Works, Distribution Central Directorate, Ministry of Water Resources and Irrigation, Cairo, Egypt
[2] Senior IWRM Resident Advisor, USAID-funded LIFE-IWRM Project managed by International Resources Group, Cairo, Egypt – eviala@iwrmeg.org – eviala@irgltd.com

about 84 billion cubic meters, Egypt's share is set by international agreement with Sudan at 55.5 billion cubic meters. Alternative water sources are limited and involve erratic and meager precipitations (average annual rainfall being less than 2 inches over most of the country), fossil groundwater whose extraction is a "one-time shot", and still expensive and underdeveloped desalination technologies.

The demand for fresh water resources has, on the other hand, steadily increased over the years, along with the population growth and industrialization, thus reducing the per capita share. Egypt recently became a water scarce country (i.e. with less than 1,000 m3/capita/year). Facing the challenge of increasing water demands with limited options to increase the supply, the MWRI has taken steps towards better water management. Concepts such as water savings and water use efficiency have now become planning priorities if not yet management objectives.

The distribution of water resources remains a centralized process, first based on proper releases from the High Aswan Dam (HAD). Released volumes are then monitored at some key locations in the Nile River while they flow downstream. After being diverted or pumped from the Nile River, water resources transit through carrier and main canals which supply branch canals. These, in turn, gravity-feed meskas (tertiary canals).

Along the Nile Valley, water distribution relies solely on gravity (apart from some initial pumping out of the Nile, or pumping into desert lands on the outskirts of the valley). In the Delta, both branch canals and meskas have over the years been lowered below field level, due to repeated excavation for desilting, and to increase the capacity of these canals. Nowadays, farmers use diesel pumps along meskas and branch canals to supply their marwas (field ditches) and plots.

Until the mid-1990s, irrigation demands were known with some accuracy since Egyptian farmers were organized through Agricultural Cooperatives and required to follow prescribed cropping patterns and calendars. In the mid 1990s, a liberalization effort was carried out by the Government of Egypt to free farmers from centrally set constraints (agricultural prices, mechanisms and entities for input purchase and crop sale, and notable crop choices). This has resulted in insignificant increases in yields and farm incomes. But water demands vary now much more from year to year, with farmers choosing their cropping patterns based on market prices, weather conditions, and input availability, among other factors.

The chief concern of regional and local MWRI managers was and still remains to ensure that water reaches the tail ends of branch canals, and that water levels are high enough to feed meskas. To that end, they operate the gates of regulators according to set or ad-hoc rotations schedules. Water levels are thus the key information upon which these managers rely for their decision-taking. In practice, the key references are the water levels recorded at the same period during the previous year(s). Past water levels are the targets, with marginal adjustments made when farmers complain about shortages or if over-supplies are observed.

This ‘status-quo’ type of management has been somewhat successful in the past, when cropping patterns and calendars were centrally planned with limited variations from year to year. Today, this management practices fail to adjust to rapid changes in the water demands. But for lack of better monitoring tools, local MWRI still rely on water levels.

In each district (on average 50,000 acres), water levels at 30-50 sites are read and reported daily (more often at the main structures or during critical periods). This massive and repetitive amount of data is then used by the MWRI managers to operate their structures and control the water distribution.

But relying on water levels means that:

- Water resources are not yet managed but simply distributed; and
- Water use efficiency is unknown (and presumably rather low, with significant over-supply in winter[3] and during night time).

PROCESS AND RESULTS SO FAR

The MWRI has recently taken steps to simplify its structure by establishing Integrated Water Management Districts (IWMDs). These IWMDs are empowered with most water management responsibilities, particularly in terms of monitoring water resources.

The USAID-funded LIFE-IWRM Project has supported this institutional reform effort. Regarding water flow monitoring, the first objectives were to train IWMD staff to:

- Become proficient in the use of equipment for regular flow measurement;
- Correlate measured flows with recorded water levels and establish calibration formulas; and
- Use these calibration formulas to translate water levels into discharges.

To achieve this, the project has:

- Provided current-meters and other flow-monitoring equipment such as boats (see Figure 1 next page);
- Prepared simple water measurement guidelines;
- Trained IWMD staff on how to operate and maintain current-meters;
- Assisted in the identification of the measurement locations for main inflow and outflow sites in each IWMD, both on canals and drains;

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[3] In winter, water needs are limited, but water levels have to be kept high to gravity feed all canals. The lack of control means that as a consequence significant volumes flow directly from the tail end of canals into the drains.

- Prepared calibration guidelines, and trained IWMD staff to apply these (see Figure 2).

Figure 1. Flow measurement staff

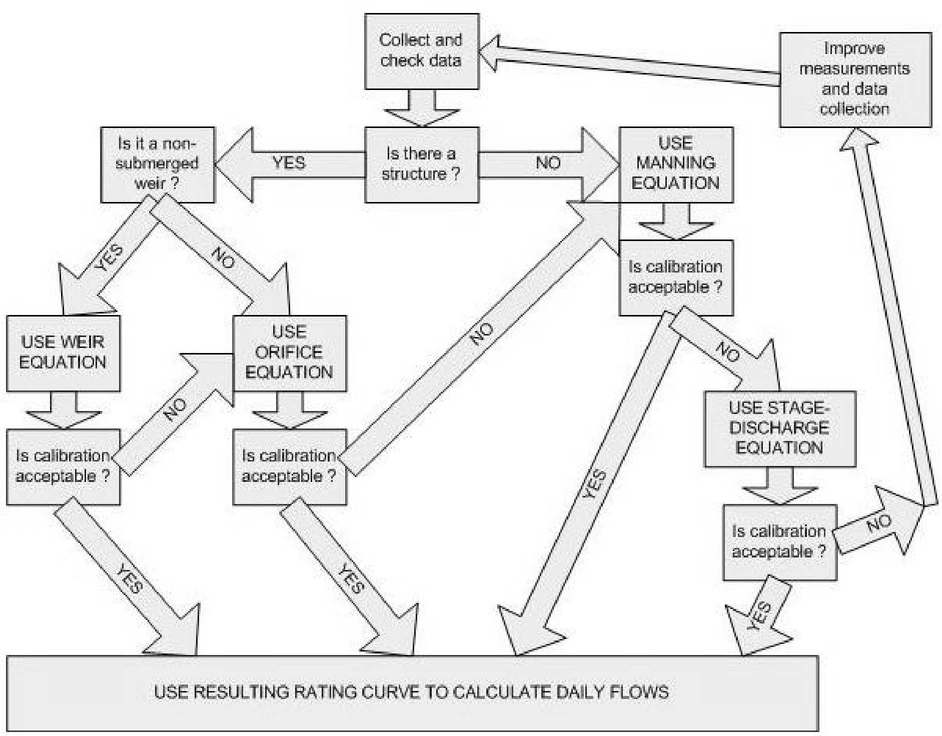

Figure 2. Decision tree for calibration of water monitoring sites

After only one year, each of the newly established 27 IWMDs (covering a total of about 1 million acres) has defined a flow monitoring network which includes the main inflow and outflow locations (from two to eights sites per district, see figure 3 below). Discharge measurements are being carried out twice a month in each of these locations, while water levels and gate openings are recorded daily.

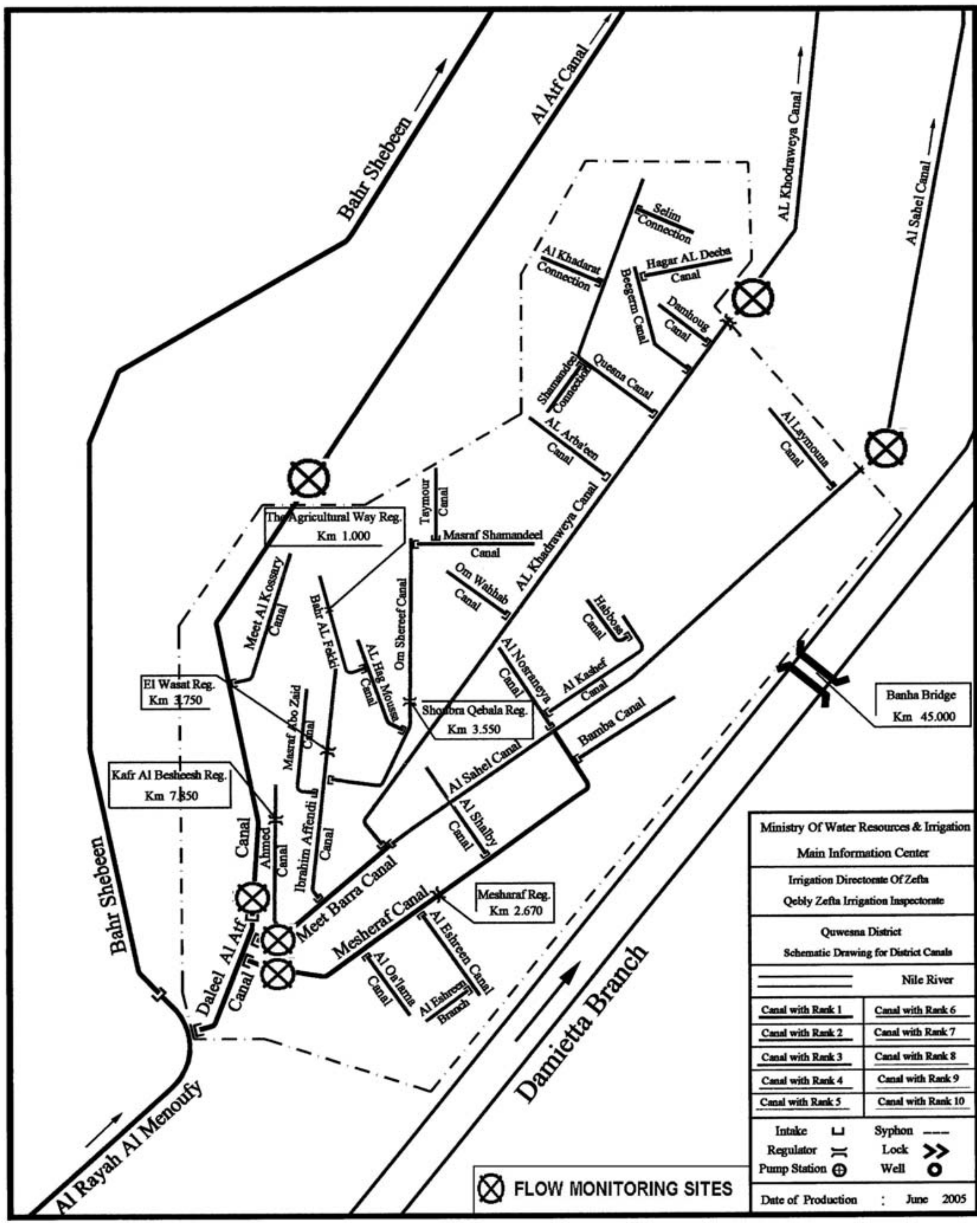

Figure 3. Flow monitoring network for Quesna District (three inflow sites and three outflow sites)

Calibration formulas (see example in figure 4 below) have been established in all of the 86 canal sites, thus allowing IWMD managers to know every day the volumes of water that have been supplied to their district.

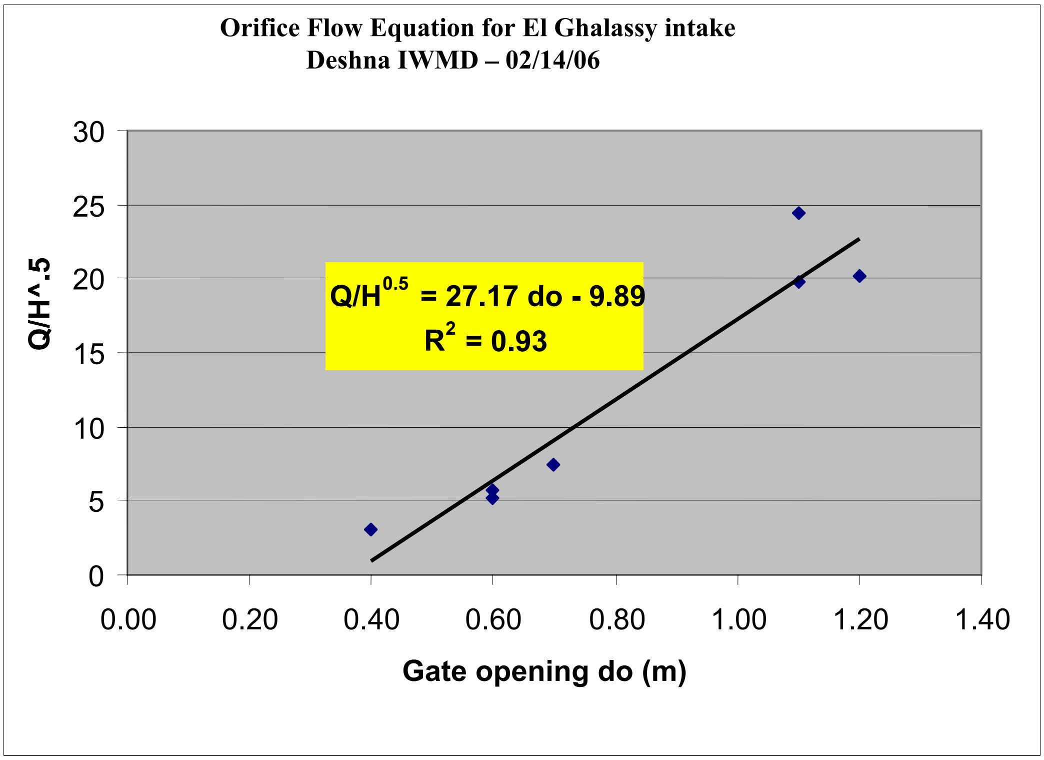

Figure 4. Example of structure calibration

The initial results of flow monitoring provided IWMD managers with the ability to compare the volumes actually received by their district with the target allocations, and thus to optimize distribution and provide feedback to the regional level. Comparing actual supplies between districts is also possible (on an area basis). But much remains to be done to ensure decentralized flow monitoring as a sustainable practice in Egypt.

REMAINING ISSUES AND NEXT STEPS

The correlation of some of the calibration formulas is poor or very poor (correlation coefficient lower than 0.85). This poor correlation is due to inaccurate data or improper recording. Collecting and recording water levels is a well established practice in Egypt, but recording gate openings is not, while essential for the proper calibration of control structures (most of the measurement sites are cross-regulators). Since the calculation of calibration formulas has demonstrated to IWMD staff how essential gate opening data is, the correlation of calibration formulas is expected to improve.

Another issue that impacts directly all data activities in Egypt is the lack of awareness of technical staff regarding the magnitude to be expected from measurements and calculations. IWMD staff and even engineers and managers sometimes submit and sign off figures whose magnitude is obviously incompatible with the relevant physical conditions. While water levels matter to both water users and managers, other water data such as discharges do not yet have much significance. Awareness raising is being provided for engineers to check the validity of their results before submission, through constant follow-up of the results.

But the best way to improve data quality is to ensure that it is being actually used for water management and decision making. This calls for both technical assistance and behavioral change[4]. The most critical objective is to lead MWRI staff to evaluate water demands, and assess water use efficiency by comparing actual supplies with the demands.

In parallel to flow measurement activities, the project is thus supporting the implementation of the Matching Irrigation Supply and Demand (MISD) program whereby crop data is being collected and used to evaluate biweekly water demands in each district. These demands are then aggregated at regional and national levels to plan the releases from the High Aswan Dam and the distribution of water resources along the Nile Valley.

While the MISD program is chiefly a national data collection effort, the project is promoting its use at district-level. The objective is to have IWMD managers compare on a biweekly basis these demands with the actual supplies they receive in their district. First results for five of the districts are shown on figure 5 below. Data accuracy needs to be seriously improved before these results can support actual decision making.

From figure 5, some observations can however be made:

- The supply-demand adequacy is reasonably good during the summer for most districts (ratios from 0.5 to 1.5); early summer sees some adjustment as the planting periods may not match the managers' expectations;
- The winter (January) closure of canals for maintenance purpose appears clearly in several districts (ratios decreasing to 0);
- The general over-supply seen during the winter period is due to the fact that water levels need to be maintained high enough in the branch canals for meskas (tertiary canals) to be supplied, while the water demands are

[4] A significant behavioral change is needed because there is currently some reluctance within MWRI to produce accurate demand and supply data (the same is true for the dissemination of water quality data). This lack of transparency and accountability is well-known in many if not all countries around the world.

comparatively low; because of limited control at the tail of the branch canals, this implies that significant volumes of water are lost to the drains[5].

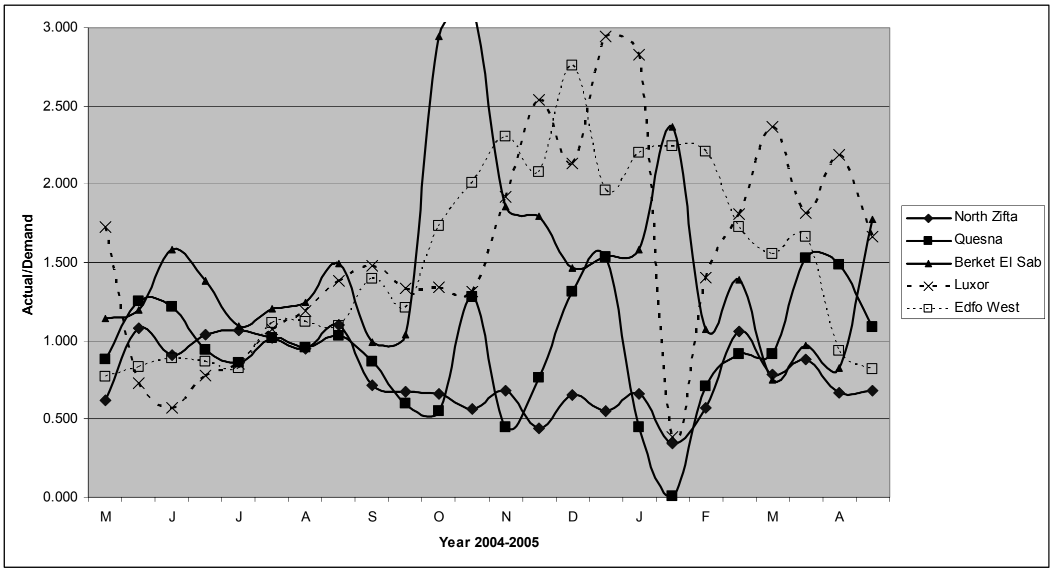

Figure 5. Biweekly actual supplies versus water demands in five districts (first three districts in the delta, last two in Upper Egypt)

A related activity is the establishment of water budgets in each IWMD (see table 1 below). The objective is again to encourage IWMD managers and their staff to think about the availability and quality of the water resources they use, and the magnitude and types of water needs present in the district. This would contribute to better water use efficiency by:

- Assessing how efficiently water is used in the district; and
- Evaluating how equally water is distributed among the districts.

This water budget would also be the basis for a proper district-level water balance (including drain flows) and most importantly for developing a district-level water management plan, where current and future demands would be compared to current and future availability of water resources.

The common thread in all these activities is to decentralize water management by training and empowering IWMD managers and staff.

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[5] It is a known fact, notably in the Delta, that the water quality in drains is significantly better in winter than in summer. This observation has led to the design and implementation of the Irrigation Improvement Project, which promotes the use of automatic downstream-control gates.

Table 1: Water budget of an Integrated Water Management District

Directorate……………………….
IWMD ……………………………

SEASONAL WATER BUDGET
(Summer Season, May 1st - September30th, or
Winter Season, October 1st -April 30th)

Water Demand (Mm3)	
1. Agriculture	
1-1 Area Served (f)	
1-2 Rice Area (f)	
1-3 Sugar Cane Area (f)	
1-3 Water Req (MISD data)	
2. Municipal	
3. Industry	
4. Other	
Total Water Demand	

Water Supply (Mm3)	
1- Canal	
2- Rainfall	
3. Drainage Reuse	
3-1 Official	
3-2 unofficial	
4. Groundwater	
4-1 Governmental	
4-2 Individual	
Total Non-conventional Water (3+4)	
Total Water Supply	

Note: While some of the data above is measured or calculated, the remainder are guesstimated (e.g., unmonitored private groundwater withdrawal or drainage reuse).

The difference between demand and supply are discussed with IWMD managers and used first to improve demand assessment and supply measurement, and second to match supply and demand.

The following indicators will also be calculated and analyzed:

Indicators	
[1]*Water Surplus/deficit (m.m3/y)*	
[2]*Water Use index*	
[3]*% of non-Conventional Water*	
[4]*Per feddan water delivery (m3/y)*	

1 water Surplus/deficit = Total water supply – total water requirement
+ for surplus
- for deficit
2. Water Use Index = Water Supply/Water Demand
3. *% of non-Conventional Water = Total non-conventional / Total supply*
4. Per feddan Water Delivery = Water Supply for Ag./Cultivated Area

CONCLUSION

The objective of decentralized flow monitoring is to provide local IWMD managers with tools to better allocate the water resources they receive and also provide intelligent feedback to their hierarchy. Decentralization is also meant to counter the heavy centralization which has always been the main characteristic of water management in Egypt[6].

The first achievements are the ability of IWMD staff to conduct regular flow measurement and to calibrate the main inflow and outflow sites of their district. IWMD managers can now compare the volumes actually received with the target allocations, and thus optimize distribution and provide feedback to the regional directors.

To maximize the use of the flow data produced, and improve water management, the project is also supporting the evaluation of water demands at district-level (MISD program) and the comparison of these with the actual supplies. A related activity is the establishment of water budgets in each IWMD, to encourage IWMD to think about the availability and quality of the water resources they use, the magnitude and types of water needs present in their district. This would contribute to better water use efficiency by:

- Assessing how efficiently water is used in the district; and
- Evaluating how equally water is distributed among the districts.

But much remains to be done to ensure decentralized flow monitoring and decentralized water management are sustainable practices in Egypt.

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[6] This centralization is not only due to the ages-old weight of the Egyptian bureaucracy and to the socialist type of management developed during the Nasser period, but also to the fact that there is only one river or one watershed to manage in Egypt. Moreover the sole water supply is Lake Nasser behind High Aswan Dam, so planning adequate releases requires centralized data collection and decision taking.

HIGH RATE IRRIGATION FOR GROUNDWATER RECHARGE

Henriette M. Emond[1]
Mark F. Madison[2]
Frank Sinclair[3]

ABSTRACT

With the establishment of Total Maximum Daily Loads (TMDLs) for Oregon rivers and increasingly stringent regulatory limits on surface water discharges, municipalities are faced with mounting challenges on discharging effluent. Effluent containing relatively high temperature levels or nutrients can not be discharged to rivers during times of low flow, principally in the summer. To address this issue, municipalities are examining other alternatives for treatment and discharge.

This paper highlights the benefits of a wastewater treatment alternative using a high rate effluent irrigation system and provides a description of a study that is being used to validate those benefits. In the study, wastewater is applied to a crop at rates greater than agronomic rates and is allowed to percolate below the root zone for eventual groundwater recharge and ultimate groundwater discharge to the nearby river. As the water slowly moves through the root zone, nutrients in the water are transformed in the soil and are taken up by the crop. The water temperature is also cooled through the interaction with the groundwater. The potential benefits from these systems include: increasing the amount of wastewater that can be applied per unit land area; improving the water quality of excess effluent irrigation water moving through the root zone which ultimately recharges groundwater and discharges to the river; and increasing the amount of water supporting the river flow as compared to strictly agronomic rate irrigation over a greater land base.

A high rate effluent irrigation program is being evaluated at two different sites in Western Oregon to collect data on this concept. The information will be analyzed to evaluate the performance of a poplar tree reuse system in polishing advanced secondary treated wastewater to remove nutrients and increase the quality of water. During the summer growing season, plots will be irrigated at 100 percent, 150 percent, 200 percent, and 400 percent of agronomic rates. Data will be

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[1] Senior Technologist, CH2M HILL, 2020 SW 4th Avenue, Suite 300, Portland, OR 97201; henriette.emond@ch2m.com
[2] Principal Technologist, CH2M HILL, 2020 SW 4th Avenue, Suite 300, Portland, OR 97201; mark.madison@ch2m.com
[3] Frank Sinclair, Superintendent Wastewater Treatment Plant, 2815 Molalla Road, Woodburn, OR 97071; Frank.Sinclair@ci.woodburn.or.us

collected to monitor the soil moisture and the vadose zone water quality associated with each of these rates of irrigation, in the root zone and just below the root zone.

Installation of irrigation and monitoring equipment for the study was begun during the summer of 2005 and 2006. Data will be collected and analyzed through the spring, summer, and fall of 2006 and 2007. Preliminary results should be available by October 2006.

BACKGROUND

Around the country, Total Maximum Daily Loads (TMDLs) are being considered as a means of controlling the loading of pollutants to our nation's rivers. With the establishment of TMDLs for Oregon rivers and increasingly stringent regulatory limits on surface water discharges, municipalities and industries are faced with mounting challenges when discharging effluent. Effluent containing relatively high temperature levels or nutrients can not be discharged to rivers over a certain load, especially during times of low flow which occurs principally in the summer.

With the proposed TMDLs and the associated new National Pollutant Discharge Elimination System (NPDES) permits, the temperature and ammonia regulations will extend beyond just the two peak summer months. Excess temperature and nutrient loading in the fall is becoming a concern. This is the time when river temperatures generally drop, fish spawning is commencing, and effluent temperatures continue to remain relatively high.

To address these loading issues, municipalities are examining a variety of alternatives for treatment and discharge. Because cost is a major consideration in any treatment plant improvement, natural treatment systems and land application alternatives are being closely examined as a means to achieving the desired constituent load reductions at less cost. In addition, the sustainable aspect of a natural treatment solution requiring less chemical additions and less infrastructure further bolsters its appeal.

One of the alternatives being considered is land application through high rate irrigation. For example, the Oregon-based research organization, SPROUT, is providing grant funding assistance to the City of Woodburn to conduct a study of high rate irrigation of poplar trees. The study is being conducted at Oregon Gardens, in parallel to a demonstration site to be established and evaluated during 2006 at the City of Woodburn's Wastewater Treatment Plant site.

Monitoring parallel research at two similar sites will increase the confidence that the data is representative of poplar tree treatment performance in the Willamette Valley. These two sites will provide information to regulators and the public and provide greater understanding of the site and monitoring designs and data to support more communities in utilizing sustainable plant systems as a part of their environmental compliance.

The target audiences for this type of project are communities interested in poplar tree technology for wastewater reuse, as well as regulating agencies involved in wastewater quality regulation. In addition, the general public will become more educated in the process of poplar tree water quality improvement and sustainable treatment.

PROJECT OBJECTIVE

The purpose of this study is to evaluate the effectiveness of using high rate irrigation of poplar trees to polish applied water percolating below the root zone.

In the study, wastewater is applied to a crop at rates greater than agronomic rates, and is allowed to percolate below the root zone for eventual groundwater recharge and ultimate groundwater discharge to the nearby river.

It was proposed that a highly monitored and controlled research site at the existing mature poplar reuse farm at Woodburn, in parallel with a comparable study at Oregon Gardens, could provide the data to determine the optimal irrigation rate for beneficial reuse and groundwater recharge. A demonstration plot of poplar trees within Oregon Gardens and a parallel portion of the research study at Woodburn's wastewater treatment plant poplar tree plantation would be both irrigated at higher than agronomic rates.

The goal of the parallel research at Woodburn and at Oregon Garden is to produce data to support irrigation rates higher than crop consumption rates. A monitored and controlled research site at the existing mature poplar reuse plots can provide the data to determine the optimal irrigation rate for beneficial reuse and groundwater recharge. The higher rate irrigation will maximize the benefits of utilizing the natural plant system as a water purification system rather than just a water consumption system. In addition, this increases the per acre capacity of a land application reuse site. This feature is particularly attractive under conditions of scarce or costly land resources.

This alternative tests the hypothesis that irrigation at higher rates remains protective of groundwater quality. If this is true, it will allow the waste water treatment plant to land apply effluent on a smaller acreage than with agronomic irrigation rates rather than discharge the same amount of water to the river. The poplar trees do not need to consume all of the water to consume the nutrients that the water contains.

As the water slowly percolates through the root zone, nutrients in the water are transformed in the soil and are taken up by the crop. Nutrients are removed and water below the root zone then may meet drinking water standards. The water temperature is also cooled through the interaction with the groundwater.

Recharge of drinking water quality water to the shallow aquifer at the site near the river can enhance the flow of cool water to the river from springs during low flow periods. The total annual volume of water discharged to the river would be similar to the current volume discharged from the outfall pipe. However, the water would be further treated by the extensive root system of the poplar trees and would be discharged through natural springs with the cool shallow groundwater. It is anticipated that the net environmental impact of higher rate irrigation would be positive.

The potential benefits from these systems include: increasing the amount of wastewater that can be applied per unit land area, improving the water quality of excess effluent irrigation water moving through the root zone which ultimately recharges groundwater and discharges to the river, and increasing the amount of water supporting the river flow as compared to agronomic rate irrigation over a greater land base. The application of agronomic-rate irrigation over a greater land base does not provide increased flow benefits to the river.

The data is intended to support the goal of gaining public support for beneficial reuse by expanding the understanding of plants as a sustainable natural treatment system. Confirmed data and information from the pilot sites will establish design criteria for a full-scale program.

PROJECT DESCRIPTION

The high rate effluent irrigation program is being tested at two different sites in Western Oregon to collect data on this concept. The information will be analyzed to evaluate the performance of a poplar tree high rate irrigation reuse system in polishing advanced secondary treated wastewater to remove nutrients and increase the quality of water. During the summer growing season, plots will be irrigated at 100 percent, 150 percent, 200 percent, and 400 percent of agronomic rates. Data will be collected to monitor the soil moisture and the vadose zone water quality associated with each of these rates of irrigation, in the root zone and just below the root zone.

The 2 sites involved in the study already have established poplar tree plantations that are approximately 8 years old. At both sites, the trees are irrigated with an above-ground solid set spray irrigation system with flow rates ranging from 0.5 to 10 gallons per minute (gpm). The total amount of water applied is dependent on duration of application.

One of the sites is located at Oregon Gardens in Silverton, Oregon. At this site, the plot is approximately 1 acre of 8- to 10-year old poplar trees, with a solid set spray irrigation system installed along the centerline of the plot. Trees are planted approximately 10 feet apart and risers are located 30 feet apart. The irrigation system is equipped with Nelson rotator nozzles with an application rate ranging from 2.5 gpm to 10 gpm. Three separate groups of trees were retrofitted with three different nozzles so that irrigation durations could remain the same for the site, with the application rate varying by nozzles.

During the 2005 summer, the irrigation ran 6 hours a day, 3 days a week during the summer months. Agronomic irrigation application occurs with the nozzles having a flow rate of 2.5 gpm. Increased irrigation application occurs on the other nozzles which have flow rates of 3.5 gpm, 5 gpm, and 10 gpm, irrigated for the same duration. During the 2006 season, a change in operating personnel resulted in deficit irrigation on most of the plot in July and part of August, but the irrigation application was increased in August and September to compensate for this shortfall.

During the winter, which is the wet weather season, the irrigation is shut off and winter rains saturate the soil. Over the course of this time, any constituents applied with the irrigation water during the summer, including nitrogen, are flushed through the soil. Data is collected on the input water quality and the water quality of the soil water during the flush.

The other high rate irrigation study site is located at the City of Woodburn Waste Water Treatment Plant Poplar Tree Plantation located in Woodburn, Oregon. Woodburn has used poplar trees for summer effluent reuse for over 8 years. The entire plantation totals 80 acres, with 8-year old and older poplar trees. The City has always irrigated the trees at agronomic rates.

At the Woodburn Wastewater Treatment Plant Poplar Tree Plantation, the high rate irrigation program will be tested on 2 of the 7-acre management units, for a total of 14 acres. The high rate irrigation may not begin until fall 2006, due to permitting constraints.

The site is irrigated with a solid set micro-spray irrigation system with risers spaced 20 feet apart down the rows and 13 feet apart between rows. Trees are spaced at 12 feet down the rows and 13 feet between rows. The irrigation system has nozzles with an application rate of 0.5 gpm. However, in the high rate irrigation section of the plantation, the nozzles are sized for flows ranging from 0.5 gpm to 1.0 gpm.

During high rate irrigation application on the demonstration plots at Woodburn, water will be applied at 150 percent, 200 percent, and 400 percent of the irrigation requirement. The high rate irrigation application will be accomplished in two ways: (1) installing higher rate micro-spray nozzles than currently in use on the Woodburn plantation to achieve a higher application rate per unit of time, and (2) extending the amount of time during which the plot is irrigated.

To achieve 150 percent of the gross irrigation requirement, the nozzles on the west half of Management Unit (MU) 11 at Woodburn, will be changed from 0.5 gpm to 0.75 gpm. The east end of MU11 will remain unchanged, and the entire MU11 will maintain a schedule matching gross irrigation requirement.

To achieve an application of 200 percent of the gross irrigation requirement, the micro-sprayers on the east half of MU12 at Woodburn will keep the same nozzles; however, the irrigation duration will be extended in order to apply twice the amount of water than required to meet the monthly gross irrigation requirement. To achieve an application of 400 percent of the gross irrigation requirement, the duration on the west half of MU12 will also be extended so that the application rate is doubled using the existing nozzles, and, in addition, the nozzles on the micro-sprayers in the west half of MU12 will be changed from 0.5 gpm to 1.00 gpm so that twice the volume of water can be applied per unit of time.

At the Woodburn plantation, the irrigation runs 2 hours a day, 7 days a week during the summer months. For the high rate irrigation study, some of the plots will be run for a longer duration to achieve the targeted irrigation rate.

Water will be applied on the poplar trees at rates exceeding irrigation requirements during the months of April through October. With the new NPDES permit, the temperature regulations will extend beyond just the 2 peak summer months. Therefore, the high rate irrigation application will be extended from the past practice of limiting irrigation to July and August.

During the study, because of the reuse systems maturity, the City of Woodburn has the flexibility to apply varying amounts of water, depending on the waste water treatment plant's discharge constraints. The current design flow to the poplar reuse system is 0.9 million gallons per day (mgd). The City has analyzed the alternative for reducing river discharge by expanding the poplar reuse system onto the waste water treatment plant's adjoining property.

As at the Oregon Garden site, the irrigation at the Woodburn site is shut off during the winter when the winter rains saturate the soil. During that time, the constituents applied with the irrigation water, including nitrogen, are flushed through the soil.

The Study Schedule

Installation of irrigation and monitoring equipment for the study was begun during the summer of 2005 and extended into the summer of 2006. Data are collected and analyzed from the winter of 2005 through the summer of 2007. Preliminary first year results should be available by October 2006.

The high rate irrigation project is scheduled to run from 2005 through the 2007 irrigation season. In the beginning of July 2005, nozzles of varying flow rates were installed and high rate irrigation begun at the Oregon Garden. Lysimeters were installed at the Oregon Garden site in the fall of 2005, and collection of soil water data began during the winter of 2006. Lysimeters were installed at the Woodburn site in August 2006, with background soil water data collected before irrigation began.

Project Participants

The project participants include staff from the City of Woodburn, Oregon Gardens, and CH2M HILL. The City of Woodburn Wastewater Treatment Plant staff will manage the irrigation system; perform the field work; and provide water quality equipment installation and monitoring, collect samples, and provide analysis. CH2M HILL staff is assisting in the monitoring equipment installation, and are primarily responsible for analyzing the data and reporting on the sites' performance. Oregon Gardens staff participates by appropriately scheduling the irrigation for high rate application and observation of the poplar tree plots. The Woodburn staff collects samples, gathers data from the lysimeters, and performs water quality analysis on the samples at Oregon Gardens site, and will do the same at the Woodburn site.

Monitoring System

For both systems, lysimeters are installed in the middle of each plot irrigated at different high rate application rates. Lysimeters are installed at a depth of 6 feet and are monitored on a monthly basis. Tensiometers will be installed at the Woodburn plot and during the summer they will be monitored weekly.

Long term weather data for precipitation and reference evapotranspiration have been obtained from a nearby weather station to verify agronomic rate irrigation application. The lysimeters will allow collection of soil pore water samples from the vadose zone below the tree roots but above the groundwater table. Water quality at this depth is expected to meet drinking water standards and may be further polished before it reaches the shallow aquifer. The sampling above the aquifer means that our soil water quality results are not impacted by groundwater. The tensiometers will provide soil moisture content data and indicate flux to groundwater.

Relevant monitoring currently being done at the wastewater treatment plant site will be incorporated into the results evaluation. The lysimeter samples are analyzed in the Woodburn water quality lab for the drinking water standards that the Woodburn lab is capable of performing, and a split sample is sent to an approved lab for the balance of the analysis.

CH2M HILL will review the lab data, make recommendations for the operation of the research site, and prepare the data evaluation report and recommendation for optimum irrigation rates for the poplar farm.

Results

The preliminary results of the nitrate concentration in the soil water samples taken at the high rate irrigation site at Oregon Gardens since January 2006 are presented in Figure 1, along with the nitrate concentrations of the application water. The center-right part of the Figure, from January to April 2006, shows the concentration of nitrates in the winter for lysimeters in 100 percent, 150 percent, 200 percent and 400 percent of agronomic rate irrigation after one season of high rate irrigation. The concentration of nitrates in the soil water range from 1.7 to 4.5 mg/L for 100 percent, 150 percent, and 200 percent of agronomic application rate during that time. However, soil water concentrations of nitrate are noticeably higher for the 400 percent of agronomic application rate. Nitrogen concentration in the applied water for the irrigation site in 2005 and 2006, and range from 4 to 11 mg/L.

A portion of the data still needs to be collected and reviewed for the latter part of the summer and the fall months of 2006.

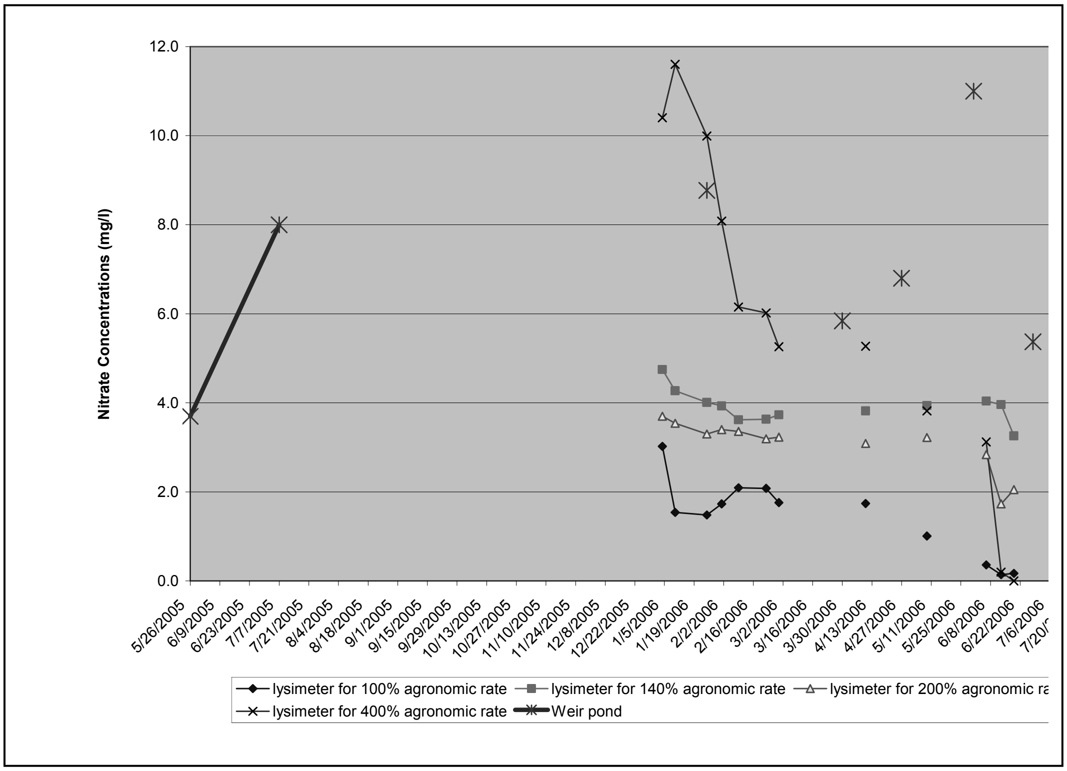

Figure 1. Oregon Poplar Tree Irrigation Applied Water and Soil-Water Nitrate Sampling

IMPERVIOUS SYNTHETIC LINING OF DETERIORATED CONCRETE CANALS — WHAT ARE THE REAL COST AND BENEFITS TO IRRIGATION DISTRICTS?

Ronald K. Frobel, P.E.[1]
A.W. Blair, P.E., Ph.D.[2]
Wayne Halbert[3]

ABSTRACT

The water crisis in arid and semi-arid agriculturally developed areas in the United States has been the focus of increasing concern and numerous studies over the past 10 years. Due to the increased public awareness and seriousness of the water crisis in South Texas along the Rio Grande during the mid to late 1990's, the U.S. Congress enacted Public Law 106-576 entitled "The Lower Rio Grande Valley Water Resources Conservation and Improvement Act of 2000". In general terms, the U.S. Congress authorized water conservation projects for Texas irrigation districts relying on Rio Grande water. One of the conservation measures was the implementation of exposed impervious synthetic linings in the reline of old deteriorating concrete delivery canals that were known to experience significant water seepage loss. The cost effectiveness of "relining" these canals was evaluated based on actual reline costs, water saved and expected O & M costs. This paper will evaluate the design, selection, effectiveness and installation of synthetic lining systems installed in various irrigation districts in Texas. Focus will not only be on water and energy savings but overall effectiveness for impervious synthetics that are designed and manufactured for installation and maintenance by the irrigation districts themselves using their own available personnel and resources.

INTRODUCTION

Historical Background of the HID, Cameron County, Texas

The District provides agricultural drainage, flood control and water supply functions to 88.3 square miles of Cameron County. The total irrigated area within the District boundaries is approximately 38,025 acres. The District outer boundary includes portions of the cities of Harlingen, Palm,

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[1]Principal, R. K. Frobel & Associates, 1153 Bergen Pkwy, Suite M240, Evergreen, CO 80439; geosynthetics@msn.com
[2]Owner/Principal, Axiom-Blair Engineering, 6012 William Cannon Drive, Suite B102, Austin, TX 78749; awblair@axiomblair.com
[3]General Manager, Harlingen Irrigation District, 301 East Pierce, Harlingen, TX 78551; waynehalbert@hidcc1.org

Valley, Rangerville as well as parts of Primera, Combs and Los Indios. The District supplies municipal water to the Harlingen Water Works Service (HWWS) through HWWS's two reservoirs, Dixieland Reservoir and Lake Harlingen. HWWS services the cities of Harlingen, Combes, Primera, Palm Valley and rural water companies, Military Highway Water Supply and East Rio Hondo Water Supply.

The Rio Grande is the only water source for the District. All of the water diverted by the District, from the Rio Grande, originates as surface water released by the International Boundary and Water Commission from Falcon Reservoir. The Harlingen Pump Station draws water from the river and disperses the water into the canal system at a starting elevation of approximately 58 feet above sea level. The terminal downstream end of the system is approximately 24 feet above sea level. The District water supply system consists of 40 miles of earthen canal, 20 miles of lined canal and 155 miles of pipeline. The system also contains 25 check structures and 44 pump sites. The District operates three reservoirs including the CCWC No. 1 Reservoir, located in the south end of the District, and the McLeod-Hood Reservoir and Bogus Lake, located in the north end of the District. The reservoirs are used as a buffer for absorbing changes in daily producer uses as well as equalization mitigating the four-day travel time of water from Falcon Reservoir.

Historically, the irrigation district has faced loss of deliverable water due to high seepage rates in unlined and old concrete lined canals and laterals, approaching over 30 percent. This, in addition to the drought conditions here and in other irrigation districts, has prompted the federal government to intitiate a program for the selection and installation of low-cost lining systems that can be installed and maintained by the irrigation district personnel without the need for specialized installers or contractors. Materials must be capable of being installed in harsh, rough conditions, resist animal traffic and be left exposed in excess of 20 years. Federal Government requests for proposals on the use of impervious linings for canal rehabilitation have traditionally focused on the following areas:

1. Technical Capability
    a. Ease of Installation (Delivery, Placement, Seaming by the ID)
    b. Damage Resistance (During Placement and Operation)
    c. Ease of Repair (Repair by ID over life of the lining)
    d. Expected Life (Manufacturer warranty for exposed conditions)
    e. Seepage control (Effective barrier material)
    f. Descriptive Literature addressing the above
2. Past History and Performance
3. Price

The final selection of a supplier is usually based primarily on technical merit, installation capability by the irrigation district personnel using their equipment, characteristics of the geomembrane material and cost. Thus, the lowest bid price may not be the principal determining factor in the final selection of the system.

HID Canal Rehabilitation Sections

The 2.45 mile irrigation canal section that was lined was an original concrete-lined canal built in 1917 and lined in the late 1950s with significant cracking and some deteriorated reaches and known high seepage loss in excess of 30% . Technical characteristics included the following:

Q (flow rate) = 72 cfs
V (velocity) = 1.32 fps
D (depth) = 4.0 ft
S (bed slope) = .00015

Side slopes were an average of 1H : 1V and base width varied between 4 feet to 8 feet. Total width of the section including anchors at top of slope was approximately 24 feet. Thus, geomembrane panels delivered to the site were required to have a minimum 24 ft. width with no longitudinal seams. Seaming in the field was to be at panel ends only and across the width of the canal section.

EPDM Rubber Geomembrane Chosen for Technical Characteristics and Low Cost

The Harlingen Irrigation District awarded the project to a material supplier of 45 mil thick Ethylene-Propylene-Diene-Monomer (EPDM) rubber geomembrane based on the above design considerations, technical evaluation factors and low cost. EPDM geomembranes have been in use worldwide for over 40 years in a wide variety of containment applications including large and small irrigation canals. Most recently, EPDM was chosen for the Ochoco and Talent Irrigation Districts in Oregon and the Tulelake Irrigation District in California, Maverick County Water Control and Improvement District, Harlingen Irrigation District and El Paso County Water Improvement District in Texas to line canal sections with significant water seepage. All of these projects utilized the irrigation district crews for canal section preparation, EPDM installation, seaming and connections to structures.

EPDM rubber geomembranes are a superior choice for use in the rehabilitation of old concrete and earth lined canals and laterals for the following reasons:

- Minimal preparation of the channel section using district equipment and personnel
- Ease of panel installation with district equipment and personnel
- Ease of seaming and repair methods by district personnel with no requirements for special equipment

- Mechanical properties to resist installation and operation stress in an exposed environment
- Attachment to concrete and steel structures (gates, turnouts, pipes, etc.) using special waterproof adhesive systems
- Lay flat (rubber friction and unit weight) characteristics to resist wind uplift/displacement
- High UV and weathering resistance backed by decades of exposed installations
- Repair and maintenance by irrigation district using simple low tech seaming techniques and repair kits
- Custom panel sizes for differing channel sections
- Installation and seaming in wet conditions
-

EPDM Geomembrane Impervious Lining Installation by the HID

EPDM factory panels were manufactured by the Firestone Building Products Company, Carmel, Indiana. The panels were custom-sized for the HID to 30 ft. in width by 200 ft. in length, folded along the length and then rolled for delivery and handling on site. Once the rolls of panels were delivered to the site, the HID deployed the panels using their own equipment and 8 person crew. District personnel fabricated a custom lifting bar which was suspended by cable from the bucket of a backhoe. The rolls of EPDM were lifted, positioned in the channel bottom and unrolled along the channel by advancing the backhoe along the channel access road.

Once the panels were unrolled and unfolded up the side slopes, they were positioned and placed into the anchor benches on both sides of the channel section. The ends of the panels were then overlapped a minimum of 6 in. and the overlap area was cleaned and primed with Firestone QuickPrime Plus. The overlap area was then tacked without wrinkles and Firestone QuickSeam tape, an adhesive tape seam system, was applied by the HID crew. The field fabricated seams were composed of prefabricated 6 in. wide rolls of partially vulcanized Firestone cover strips with adhesive backing. Once the strip was placed and centered on the overlap, it was pressed down onto the two adjacent panels with constant hand roller pressure to ensure complete adhesion.

Advantages of using the patented tape seam system include:

- Designed for remote areas and can be installed in cold and hot temperatures
- No specialized welding equipment, hot air guns or supporting electric generator equipment is required
- Components are simple and can be stored at irrigation district shops for future use
- Seaming requires no specialized training (HID crew received on-site instruction)

- Resultant seam is a continuous 3 in. bond to panel edge with high peel and shear strength. Seam area will resist movement under load of over 100 percent without affecting the waterproof integrity
- The same seam methods are used for repair patches by HID maintenance crews.

During the placement of panels, it was noted that the EPDM sheet material was not susceptible to wind uplift even by high winds which are a frequent occurrence at this site. The EPDM rubber sheet conforms readily to the rough concrete, lays flat and adheres to the concrete due to surface friction, unit weight and flexibility (conformance to substrates).

Once the panels were in place and seamed, the HID crew placed soil in the anchor trenches and compacted the material at top of slope with motor grader wheel loading. Cross anchorage was provided by saw cutting into the concrete, placing the EPDM in the cut trench and backfilling with low slump concrete to provide a smooth transition.

Although the EPDM lining is performing very well, the lined sections of the canal need to be inspected periodically so that any cuts or breaks in the panels caused by mechanical impacts or animals can be patched prior to any water flowing under the panel. A tear in an EPDM panel has limited resistance to propagation in flowing water and should be repaired quickly. Repairs are easily accomplished by district crews using Firestone QuickPrime Plus and the adhesive tape seam system.

<u>Cost-Benefit Analysis in the use of an Impervious Lining over Concrete</u>

Table 1 lists the economic information regarding the canal lining project described previously. The capital investment included all costs associated with the project including engineering and project administration. The expected useful life of the EPDM liner was assumed to be 20 years and that there would be a net reduction in maintenance cost of approximately $500 per mile of canal lining. The annual water savings were estimated based on the seepage rate measured using hydrostatic or ponded water tests. All water used by Harlingen Irrigation District is pumped from the Rio Grande into the Harlingen Main Canal and then conveyed by gravity to approximately 38 secondary lift stations. The energy savings were estimated based on the energy used per acre-foot to pump water from the Rio Grande into the Main Canal.
The minimum value of the conserved water was estimated on the average spot market rates for irrigation water in the Lower Rio Grande Valley. The spot market rates are based on single-time purchases of the use of irrigation water as compared to long term contract rates for the lease or purchase contracts for the permanent sale of the water right. Spot market rates for irrigation water are typically have a lower cost per acre-foot than raw water for municipal use.

The minimum value to cost ratio for the lining project was 1.35 and the annual net revenue of the project that would have resulted if the conserved water was sold on the spot market was $3,363.00

Table 1. Canal Lining Economic Information

Description	
Initial Capital Investment ($)	$ 141,744.00
Expected Useful Life (yrs)	20
Net Change in Annual O & M Cost ($/yr)	$ (1,225.00)
Net Changes in Annual Energy Cost ($/yr) @ $0.10 $/kwhr	$ (1,476.00)
Annual Cost of Capital Investment @ 6.0% ($/yr)	$12,357.89
Net Annual Cost ($/yr)	$ 9,656.89
Estimated Water Savings (ac-ft/yr)	434
Annual Cost (ac-ft/yr)	$ 22.25
Estimated Minimum Value of Conserved Water (Spot Market Irrigation, $/ac-ft)	$ 30.00
Annual Gross Revenue that would result from Marketing Conserved Water	$ 13,020.00
Minimum Value to Cost Ratio	1.35
Annual Net Revenue that would result from Marketing Conserved Water	$ 3,363.11

SUMMARY

The HID successfully installed an exposed EPDM geomembrane system using custom manufactured panels, HID personnel for installation and seaming and HID equipment for placement of panels and the concrete preparation and anchor trench backfilling. The combination of low cost and user friendly materials that can be installed by irrigation district personnel with minimal training and no specialized equipment is an outstanding alternative to other systems.

The HID is typical of many irrigation districts in the South West and Western United States where conveyance channels are unlined or concrete lined but in very poor conditions with many losing between 10 and 50 percent of the deliverable water due to seepage during the irrigation season. With water costs increasing and available water in short supply (especially during dry years or federally mandated allocation restrictions), irrigation canals and laterals are being evaluated for lining with exposed geomembrane systems. There are over 16,100 miles of main canals and over 27,000 miles of laterals in the western United States alone. Of these, only approximately 15 percent are lined with concrete, compacted earth or geomembranes. Although all reaches of earth lined or concrete lined canals or laterals do not need an impervious lining, the potential of those that will need rehabilitation to save valuable irrigation water is indeed very large. The water crisis is real and is here to stay and we must address water conservation with a variety of technologies including the implementation impervious lining systems that have a track record of proven effectiveness, longevity and are economically advantageous to irrigation districts.

Photo 1. Typical Condition of Deteriorated Concrete Canal Section

Photo 2. Example of Seepage Adjacent to Cracked Concrete Irrigation Canal

Photo 3. Placement of EPDM Panels by the Irrigation District

Photo 4. Typical Lined and Seamed Section

DESIGN AND INSTALLATION OF A FLUME TO MONITOR SPRING DISCHARGE AT THE HEADWATERS OF THE VERDE RIVER

Curt Kennedy[1]

ABSTRACT

Many rivers in the Southwestern US are under threat of declining base flows caused by groundwater withdrawal and poor forest/watershed management. This paper describes the design and installation of a Critical Depth Flume (Flume) to accurately monitor base flows on the upper Verde River, located in North Central Arizona. Although Flumes are very common and accurate flow measurement structures, there application in native channels has been limited. Some of the problems associated with using a Flume in native channels are: maintenance, cost, flood damage, sedimentation, shifting channels, unstable substrate, and limitations due to the Endangered Species Act and 404 permit. This paper illustrates how these issues were addressed at one location in North Central Arizona.

BACKGROUND

At its origin the upper Verde River emerges from a series of springs. Within about a quarter mile, the flow transitions from zero too 20 cfs. The Big Chino Aquifer is the primarily source of this spring water. The river and aquifer are connected through a geologically complex area at the headwaters.

Record population growth in this region has resulted in increased pumping that threatens to lower the water table within the Big Chino Aquifer. Currently the water table in the Big Chino Aquifer is approximately 25 feet above the water surface elevation of the Verde River; as the water table is lowered, flows in the river will be reduced. If the water table is lowered more than 25 feet, flow in the upper reach of river could stop or become intermittent. The Cities of Prescott and Prescott Valley have committed to mitigate any impacts from pumping. The flume is designed to access any base flow impact.

FLUME DESIGN

Flume design at this location was aided by an almost constant discharge associated with the springs. An emphasis was placed on resolution where small changes in discharge would result in measurable changes in water surface elevation within the flume. This was accomplished with side contractions to narrow the throat of the Flume. Other design considerations included:

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[1] Senior Analyst, Salt River Project, Mail Station PAB112, P.O. Box 52025, Phoenix AZ. 85072-2025, cgkenned@srpnet.com

- Avoiding interference with the natural sediment transport.
- Maintaining the drop in water surface that occurs in the ambient pool-drop channel conditions.
- Surviving large floods associated with the 1,500 square mile watershed upstream of the flume (flows of 25,000 cfs have occurred at this location).
- Avoiding installation of a hazard to kayakers, rafters or other river enthusiasts. (This too often is not considered when designing features in natural channels.)
- Maintaining safe flow conditions for the public and recreation.
- Developing a design that would allow flow to return to the channel where the flow is located after flood events.
- Maintaining the natural energy slope associate with the channel to avoid submerging the flume.
- Avoiding obstructions/structures that would result in scour during high flow events that could compromise the flume’s structure and stability.
- Creating a low maintenance measurement flume – one that would not retain silt or aquatic weeds that would require machine cleaning.
- Minimizing cost – the budget for design and construction was $75,000.
- Developing permits (404, section 7 ESA) that would allow maintenance and refurbishment of the flume without re-permitting.

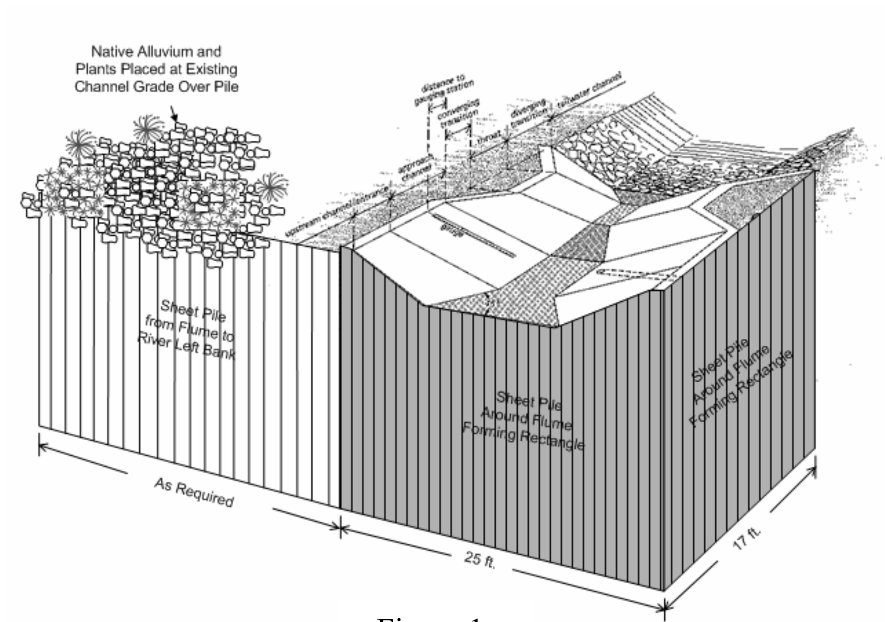

Figure 1.

WinFlume [add reference] and HEC-RAS [add reference] were used to design the flume in addition to standard manual analyses for specific channel characteristics. Because this flume would be located in a native channel, virtually every decision required evaluation from an overall system perspective. This requires an interdisciplinary understanding of the systems. For example, too much change in water surface will result in pooling upstream and scour downstream. To maintain equilibrium conditions of the channel, the flume should be designed to guard against submergence by increasing the change in water surface occurring through the flume.

To obtain resolution within the range of known spring discharges, the flume was designed with side contractions. Side contractions have the benefit of not impeding sediment transport and allowing precise control of the Froude number within the flume's approach channel. To accommodate higher flows, the side contracted section was incorporated into a complex trapezoidal design (Figure 2). This allows reasonable accurate measurement up to 100 ft^3/sec. with precise measurement in the range of 10 ft^3/sec. - 25 ft^3/sec, flow rates greater then 100 ft^/sec are not measured. The drawback to complex trapezoidal design is they can be hard to build in the field. To overcome this, each transitional section (like the one shown in Figure 2) was precisely fabricated in a steel shop prior to installation in the field.

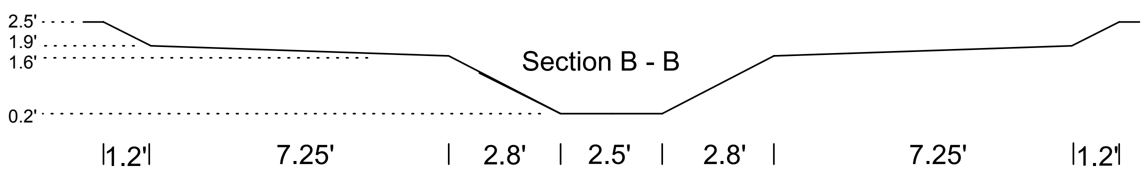

Figure 2

To provide an easy-to-use find reference point for the instrumentation and field gauges, a small Sill (0.20') was incorporated into the design. Making the end points of each section terminate at the same elevation made installation easy.

Once a satisfactory flume design was obtained, the channel and flume were modeled in HEC-RAS. This allows the designer make assessments regarding the river's response to different flood flows.

It is critical that the placement of a small flume within the larger stream channel not disrupt the system equilibrium. This is a balancing act. Streams are dynamic by nature, and you must constrain certain processes to assure viable operation of the flume. The items evaluated during the design of this flume were:

- Channel material and alluvial particle size distribution.
- Recurrent interval of floods

- Channel constraints (mountains, rock outcrops)
- Distribution of riparian growth
- Channel slope
- Distance between riffles and average fall at riffles
- Depth of unconsolidated channel alluvium

The channel in the area of the flume was formed by relatively frequent high energy floods. The average particle size is medium to coarse gravel with some infrequent large boulders; there is little or no sand, slit or clay. To minimize the exposure of this flume to the destructive erosional forces in this region; the flume was located in a reach of river that opened to a large, wide alluvial terrace. This choice has the benefit of exposing the flume to lower flow velocities during flood flows. The negative aspects of this choice are that the flume will be constructed on unconsolidated alluvium, and that the channel slope could be quite variable through time due to the absence of stable structure.

Photo 1.

Effectively addressing the issues of constructing on an unconsolidated alluvial material and channel slope variability are critical to the longevity and accuracy of this flume. At this site we chose to use sheet piles to control these variables. Photo 1 shows the initial installation of sheet piles to develop a dry working area and define the perimeter of the flume. Latter in construction sheet piles would be used to form sub-surface walls to control scour, return the channel to the flume after floods, and stabilize the channel's slope. Photo 2 shows the outline of the concrete flume prior to restoring flow. The workers are cutting sheet piles to the finish contour of the concrete.

Photo 2.

Photo 3.

Photo 3 shows the site after a 25,000 cfs flood flow with the scour walls exposed. These walls serve two minimize scour and return the base flow channel to the flume. Note that the walls are angled downstream, and are sloped up from the base flow channel to the high flow channel banks. This forces the channel to return to the flume; as the flood flows recede, water moving downstream is forced to change direction back toward the low flow channel as it brakes over the pile wall. This process continues as the flood flows recede.

Determination of how deep to construct the scour walls was done with a scour depth analysis. Because the scour process is quite variable, two different methodologies were used to predict scour depth and then compared. The primary factors controlling scour depth are flood size and particle size and distribution. At this site scour depths were predicted to reach 3 meters, this 3 meter value was used as the depth of the subsurface wall.

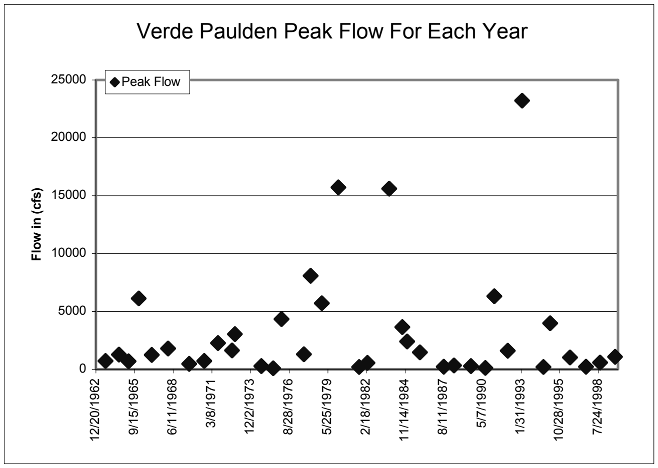

Figure 3.

Another function of the scour walls is to control channel slope, which is critical in preventing submergence of the flume. At this location the channel cross-section was elevated 0.3 foot to guard against submergence and increase the downstream fluid velocity to prevent deposition of sediments. To maintain channel stability, par ticular care was taken to match the natural distance between riffles and the fall at each riffle. For this reason this flume was constructed at the natural location of a riffle.

PERFORMANCE

This flume has been in service and monitoring base flow since June of 2004.

Under normal base flow conditions the spring's discharge as measured through the flume has shown the diurnal patterns associated with plant evapotranspiration. One notable exception occurred consistently on Sunday afternoons where a 0.5 cfs – 1 cfs drop in flow would occur. It turns out that marijuana growers were pumping water from the Verde River upstream of the flume, this stopped when the field was discovered by law enforcement.

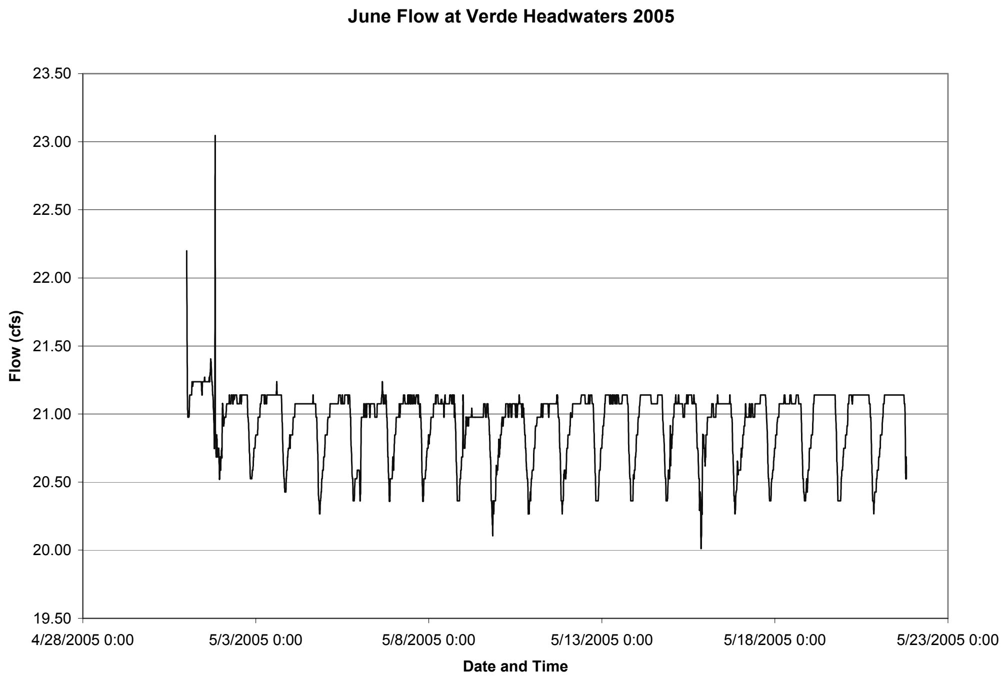

Figure 4.

The flume's first winter/spring runoff season was notable in that three major flood flows occurred; the highest flow being approximately 25k cfs. Photo 4 was taken approximately five miles upstream of the flume by a local resident at Sullivan Dam. These floods exposed the tops of the sheet pile walls and shorted the satellite communicator. The sheet piling was covered with native alluvium by a backhoe in approximately ½ day, the satellite communicator was replaced. The flume and instrument package were unharmed.

Photo 4.

This site has produced a high quality record of base flow data for this reach of river. This information will provide water resource managers the data needed to protect and manage this springs that provide flow to this river for year to come.

OPTIMAL ALLOCATION OF LIMITED WATER SUPPLY FOR A LARGE-SCALE IRRIGATED AREA — CASE STUDY

Daniele Zaccaria[1]
Nat Marjang[2]

ABSTRACT

A study is conducted on a large-scale pressurized irrigation scheme located in southern Italy. The ultimate goal is identifying optimal allocation of limited available water supplies under the existing cropping pattern scenario and infrastructures. The irrigation scheme was originally designed some 30 years ago to allow extensive agricultural development for the area. Nevertheless, major changes in cropping patterns occurred. As a result, the current operating conditions and irrigation demand patterns are different from the original design. Different levels of limitation in water resources are considered to account for climatic trends. Crop irrigation requirements were preliminarily mapped, under three different climatic conditions. Then the allocations of different levels of limited water supply are analyzed. Economic objectives as well as physical, social and environmental constraints are considered using optimization model. Tariff rules for irrigation water are discussed as related to different water management options. Optimal conjunctive use of surface and groundwater for the different time periods of the irrigation season are also analyzed. Based on the results, practical recommendations about the operation of the existing infrastructures as well as modernization options are provided. Results indicate the importance of data monitoring, data interpretation and the need for quantitative-based models to improve decision-making and the economic sustainability of irrigated agriculture.

INTRODUCTION

A large-scale irrigation scheme located in Southern Italy and managed by a local Water Users Association (WUA) is investigated. The irrigation system serving the study area was originally designed some 30 years ago to allow for extensive agricultural development. Changes in cropping patterns occurred as a result of

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[1] Department of Irrigation Engineering, International Center for Advanced Mediterranean Agronomic Studies (CIHEAM – IAM Bari) - Italy, currently Ph.D. candidate at Department of Irrigation Engineering, Utah State University, Logan, Utah 84322-4105, USA; zaccaria@cc.usu.edu

[2] Faculty of Engineering, Kasetsart University - Thailand, currently Ph.D. candidate at Department of Irrigation Engineering, Utah State University, Logan, Utah 84322-4105, USA; natmarjang@cc.usu.edu

favorable agro-climatic conditions and of market trends; also progresses in farming and irrigation practices were achieved. Consequently, current farmers' irrigation demands are different from those foreseen during the design stage and from the ones existing since the system was first put into service.

On the other hand, different levels of limitation in available water supply for irrigation may occur as a result of climatic trends. The combination of different possible conditions of water demand and supply might require different management strategies in order to allow satisfactory economic returns from farming activities and to maintain a sustainable irrigated agriculture in the area.

OBJECTIVES AND APPROACH

The main purpose of this study is to develop a model for optimal allocation of limited available water supplies to a large-scale agricultural area, under the existing cropping pattern conditions and for the existing irrigation infrastructures. Crop irrigation requirements were mapped under three different climatic conditions, by using a soil-water balance model. This preliminary task involved analysis of historical climatic data series (1959-1994) and the application of a probabilistic approach to identify three scenarios characterized by three different levels of climatic water demand (average, demanding, very-high demanding). Based on this spatially-distributed set of information, allocations of different levels of limited water supply were simulated for each of the three climatic scenarios.

The simulations were conducted on a volumetric basis for the whole irrigation season. Economic objectives as well as physical, social and environmental constraints were considered within the optimization model**.** Yield response to irrigation was estimated by means of the Stewart model (Doorenbos and Kassam, 1979). Finally, optimal conjunctive use of surface and groundwater for the irrigation season was analyzed.

BACKGROUND ON THE STUDY AREA

The analyses were carried out on the areas served by the "Sinistra Bradano" large-scale irrigation system, which is located in the south-eastern part of the Italian peninsula. This system covers a total topographic area of 9,500 ha. The physical boundaries of the study area as well as its location, shape, topographic conditions and extent are reported in Figures 1 and 2.

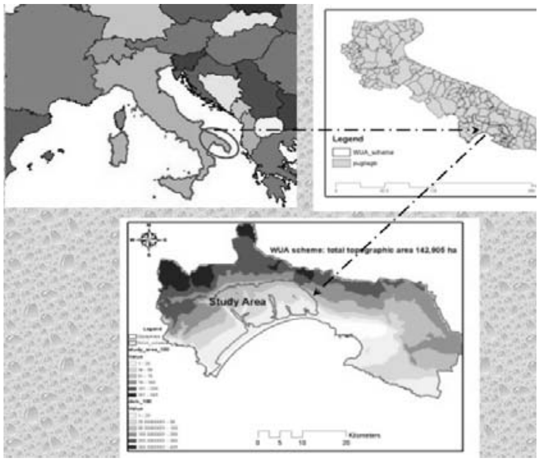


Figure 1. Location and extent of the area of interest

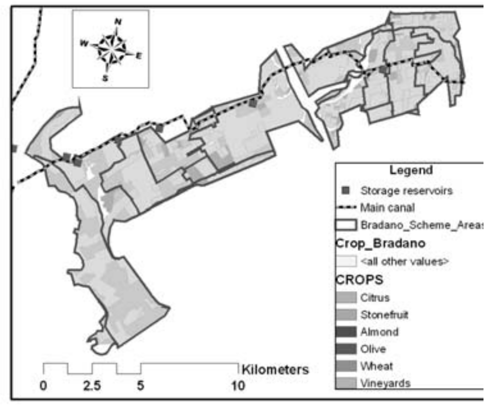


Figure 2. Representation of the "Sinistra Bradano" irrigation scheme

Main irrigated crops are table grapes, citrus, olive and summer vegetables, as shown in Table 1 and from Figure 2. Most of the farms utilize trickle irrigation as predominant method, while in some limited areas sprinkler irrigation is still utilized for citrus and summer vegetables.

Table 1.Existing cropping pattern in the study area.

Crop	Sinistra Bradano (ha)
Table grapes	3753.4
Citrus	2208.3
Vegetables	2184
Olive	431.9
Stone fruit	44
Almond	14.4
Total (ha)	**8636**

Source*: Water Users Association « Stornara e Tara », 2001*

Due to favorable agro-climatic conditions, agriculture in the area is intensive and highly market-oriented. Climate is semi-arid with an average yearly precipitation of about 550 mm, which are poorly distributed along the months. Therefore profitable farming is strongly dependent on irrigation. As a matter of fact, collection of water fees is tightly linked to the quality of irrigation services provided by the WUA. The typical irrigation season lasts from the beginning of April to mid November. The hydraulic scheme is composed of a main canal conveying water from a regional dam to four storage and compensation reservoirs, which serve ten irrigation districts. From each of these reservoirs, district pressurized distribution networks originate for delivering irrigation water to the farms. Figure 2 shows the main features of the irrigation scheme.

Irrigation distribution network is operated by rotation delivery schedule. The usual rotation is based on a 10-day shift. At present, distribution of irrigation water to farms, as reported by many farmers, is too restrictive and not timely matching the actual crop water requirements. As a result of all the above issues, during the last 10 years a large number of water users started developing their "private water sources" by drilling on-farm irrigation wells (nearly 6,000 wells). This led to over-pumping from aquifers. Further environmental concerns are saline intrusion in groundwater and an increasing process of salt build-up in the soils. Therefore, a sound estimation of agricultural water demand is strongly needed as initial step for improving water management in the study area. The final goal of this plan is maximizing the net benefit for the entire irrigated area. This operational plan represents the general objective of the present study.

MODEL FORMULATION

A non-linear programming model was developed to achieve the optimal allocation of available water supply among the different cropped areas. The model was developed based upon data and information. Information on crop water requirements were generated by running a soil-water balance model on each identified simulation unit. Simulation units are areas characterized by the same crop, soil and climatic conditions.

Objective function

The objective function for the developed model is the following:

$$NetBenefit = \sum_{i=1}^{n} \left[\left(Ya_i * MV_i * A_i \right) - \left(PC_i * A_i \right) - (Ia_i * 10 * A_i * C_w) / S_{eff} \right] \qquad (1)$$

where $\boldsymbol{Ya_i}$ is the actual yield of crop $\boldsymbol{i}$ (ton/ha), $\boldsymbol{MV_i}$ is the averaged value on the local market for the crop $\boldsymbol{i}$ (\$/ton), $\boldsymbol{A_i}$ is the area of crop $\boldsymbol{i}$ in hectares, $\boldsymbol{PC_i}$ is the production cost of crop $\boldsymbol{i}$ (\$/ha) excluding the cost of irrigation water, $\boldsymbol{Ia_i}$ is the amount of irrigation water required by crop $\boldsymbol{i}$ to obtain the actual yield (gross irrigation requirement, mm), $\boldsymbol{C_w}$ is the unitary cost of water (\$/m^3) and $\boldsymbol{S_{eff}}$ is the overall efficiency of the irrigation system, assumed to be 80%. In this model the crop water requirements are net amounts. The related gross amounts are considered in the objective function, where the overall irrigation system efficiency is accounted for.

Set of Constraints

Area constraints. There are two sets of areal constraints imposed.
The first one concerns the area occupied by each crop included within the cropping pattern. In the preliminary study on crop water requirements, 42 different simulation units were identified and coded on the basis of crop-type,

soil-type and the climatic sub-area they are located in. The total area was imposed as maximum area constraint for each code within the model. The area constraint for each simulation unit is in the form of:

$$\sum_{j=1}^{m} A_{ji} \leq A_i \qquad (2)$$

where A_{ji} represents the area of the different plots belonging to the same simulation code i.

1. The second type of constraint was included in the model to ensure that the sum of areas relative to different simulation units does not exceed the total cropped area served by the irrigation scheme. This constraint is in the form of:

$$\sum_{i=1}^{n} A_{ci} \leq TA_{serv} \qquad (3)$$

where A_{ci} represents the area of the different simulation codes and TA_{serv} is the total area served by the irrigation scheme.

Yield constraint. Water deficits in crops and the resulting water stress on the plant have an effect on crop evapotranspiration and crop yield (Doorembos and Kassam, 1979). The yield reduction depends on the level of water stress through the following relationship:

$$\left(1-\frac{Ya}{Ym}\right) = k_y * \left(1-\frac{ETa}{ETm}\right) \qquad (4)$$

where Ya is the actual yield (ton/ha), Ym is the maximum obtainable yield (ton/ha), k_y is the yield response factor (dimensionless), ETa is the actual evapotranspiration (mm) and ETm is the maximum evapotranspiration (mm). Maximum-yield constraints were imposed in the model to make sure that the actual yield of each crop does not exceed the maximum yield obtainable. In this constraint, an overall efficiency of the irrigation system of 80 % was also accounted for. The maximum harvestable yield for the different crops and Yield reduction factors are reported in the Table 2.

Table 2. Seasonal Yield reduction factors and Maximum Yield for different crops

Crop	**K_y**	**Max Yield (Ton/ha)**	**Crop**	**K_y**	**Max Yield (Ton/ha)**
Almond	0.80	2.5	Stone fruit	0.80	25
Citrus	0.90	30	Table grapes	0.85	35
Olive	0.80	20	Vegetables	1.10	40

Water Availability constraint. Two water availability constraints were set in the model:

1) The first one relates to the water supplied by the Water Users Association. A volumetric constraint was imposed in the model to ensure that the total volume resulting from the optimal water allocation among the different areas of the irrigation scheme does not exceed the total water supply available from the WUA for the whole irrigation season.

$$\frac{\sum_{i=1}^{n} CIR_i}{S_{eff}} \leq TW_{wua} \qquad (5)$$

where $\boldsymbol{CIR_i}$ is the seasonal irrigation requirement for each crop $\boldsymbol{i}$ [which is given by (ETc-Eff.Rain)], $\boldsymbol{TW_{wua}}$ is the total water available by the Water Users Association.

2) The second constraint relates to the total seasonal volume that can be withdrawn from the groundwater. The concept of Safe Yield of aquifer is applied in this water modeling project and ground water is only used for emergency and supplemental irrigation when the water from WUA is not sufficient relative to water demand. The allocated supplemental volumes to deficit cropped areas do not exceed the seasonal Safe Yield of the aquifer. This constraint is given by:

$$\frac{\sum_{i=1}^{n} CIR_{GW\,i}}{Application\ Efficiency} \leq TW_{GW} \qquad (6)$$

where $\boldsymbol{CIR_{GWi}}$ are the irrigation deficits for each crop $\boldsymbol{i}$ to be compensated by using groundwater, $\boldsymbol{TW_{GW}}$ is the seasonal Safe Yield from the aquifer and ***Application Efficiency*** is assumed to be 90 %.

Constraint on equity distribution. This was done in order to allocate a 50 % fraction of the total available water supply from WUA on the basis of equity. The selected equity criterion is to deliver to each cropped area an amount of water corresponding to 60 % of the maximum harvestable yield. The other 50% of available water supply from WUA is delivered to those farmers willing to pay increasing unit prices for increasing water volumes.

$$ETci_{(0.60Y)} \geq \left[\left(\frac{Y_{60}}{Y_{max}}\right) - 1 + k_y\right] * \frac{ETc_{max}}{k_y} \qquad (7)$$

$$\frac{\sum_{i=1}^{n} ETci_{(0.60Y)}}{Overall\ Efficiency} \leq 0.50 * TW_{wua} \qquad (8)$$

where $\boldsymbol{ETci_{(0.60Y)}}$ is the crop evapotranspiration corresponding to 60 % of the maximum yield for each crop ***i***, $\boldsymbol{Y_{max}}$ is the maximum harvestable yield and $\boldsymbol{Y_{60}}$ is 60 % of $\boldsymbol{Y_{max}}$.

Net benefit constraint. The last constraint is related to the net revenue obtained by farmers for each simulation unit. This constraint basically prevents any cropped area getting negative net benefit. This is related to the cost for any unit of water utilized by farmers.

$$NB_i \geq 0 \qquad (9)$$

where ***NBi*** is the net benefit for each cropped area ***i***.

Sources of information and data description

As previously pointed out, information relative to crops grown in the area were obtained from different sources. 1) "Stornara e Tara" Water Users Association – Agronomic Division; 2) Istituto Nazionale di Economia Agraria (INEA-RICA), 3) Agricultural Office – Apulia Region, 4) Chamber of Commerce of the Province of Taranto, 5) Private agriculture consultants, 6) Public and private extension service officers, and 7)Web sources

Harvestable Crop Yield. The data in Table 2 represent the 5-year averaged maximum obtainable yield for the different crops normally grown in the area served by the "Sinistra Bradano" large-scale irrigation scheme.

Market value of crop productions. These data represent the last three season average of what was normally paid to farmers in the study area. Crop market values are reported in the following Table 3. As for summer vegetables, the values are the average between the three main crops, namely bell pepper, eggplant and water melon.

Table 3. Local market values of crops grown in the study area

Crop	***Yield (Ton/ha)***	***Price (EU/tons)***	***Price ($/tons)***	***Market Value ($/ha)***
Almond	2.5	945.0	1228.5	3,071
Citrus	30	400.0	520.0	15,600
Olive	20	700.0	910.0	18,200
Stone fruit	25	320.0	416.0	10,400
Table grapes	35	500.0	650.0	22,750
Vegetables	40	287.5	373.7	14,950

** Conversion 1 Euro = 1.30 US Dollars*

<u>Crop production costs.</u> Crop production costs relate to all farming practices necessary to achieve high quality yield as reported in Table 4 and do not include cost related to irrigation.

Table 4. Production costs for crops grown in the study area

Crop	***Total farming cost (EU/ha)***	***Total farming cost ($/ha)***
Almond	1,000	1,300
Citrus	8,000	10,400
Olive	7,000	9,100
Stone fruit	900	1,170
Table grapes	12,500	16,250
Vegetables	4,335	5,633

** Conversion 1 Euro = 1.30 US Dollars*

<u>Cost related to irrigation.</u> In the study area water is currently charged by the managing body (WUA) based on the cropped area served. This basically means that also irrigation represents a fixed cost regardless the water volume actually utilized by farmers.

For the present water modeling project a different tariff rule was considered with the aim of optimizing allocation of limited water supply but also to improve the efficiency of water use at the farm level. For these reasons water is charged on a volumetric basis with increasing rates for increasing volumes withdrawn by farmers. These rates are presented in Table 5. Also, according to the water cost applied to different classes of consumption, the resulting unitary cost for incremental steps of volume was calculated and plotted (graph presented in Figure 3).

In case farmers utilize groundwater for irrigating their crops, the unit cost of water is estimated on average at 0.39 $\$/m^3$ (0.30 EU/m^3).

Table 5. Unit prices for water for the different classes of volumes

Water volume (m^3)	***Unit cost (EU/m^3)***	***Unit cost ($\$/m^3$)***
< 2,000	0.113	0.146
2,000 – 3,000	0.225	0.292
> 3,000	0.30	0.390

** Conversion 1 Euro = 1.30 US Dollars*

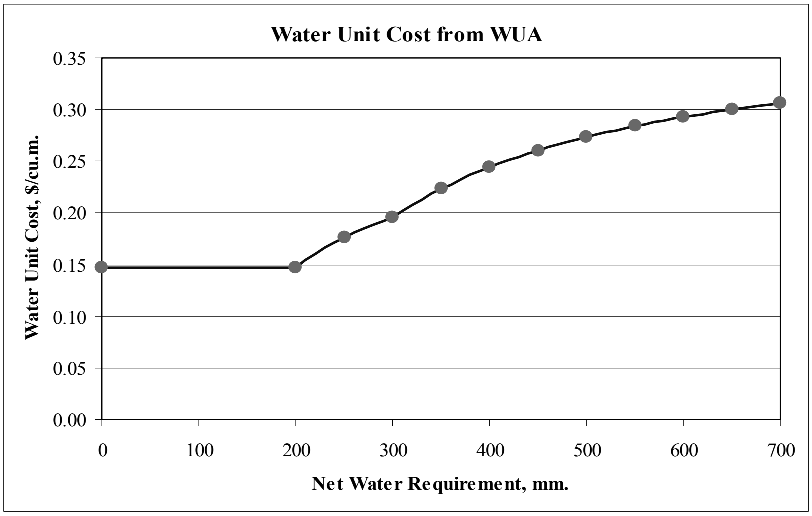
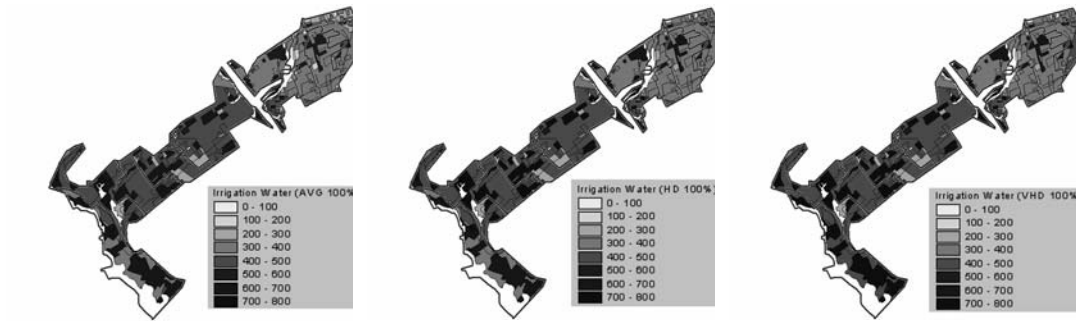


Figure 3. Plot of the unitary cost for the different water volumes withdrawn by farmers

RESULTS AND DISCUSSION

Crop irrigation requirements were calculated and mapped under three different climatic scenarios (average, hi, and very-high demand) corresponding to probability of occurrence of 50 %, 75 % and 95 %. These represent the basic water demand scenarios and are reported in Figures 4.

As for water supply, six different scenarios were simulated starting from full satisfaction of crop water requirements (100 %) up to the most critical situation considered, which corresponds to a water availability of only 50 % of the total water demand. For these, magnitude of deficits was computed. On these water deficit scenarios, a second run of the model was conducted in order to find the optimal allocation of ground water. The model was in fact developed in such a way to give priority of use to water from the WUA. Only when the available water supply from WUA is not sufficient to adequately serve the whole area a supplemental use of groundwater is allowed and for volumes corresponding to the quantified existing water deficit. This approach resulted in computation of the combined net benefit and in developing a sort of seasonal plan of conjunctive use of surface and groundwater resources for the whole scheme.



Average demand High-demand Very-high demand

Figure 4. Map of crop water requirements

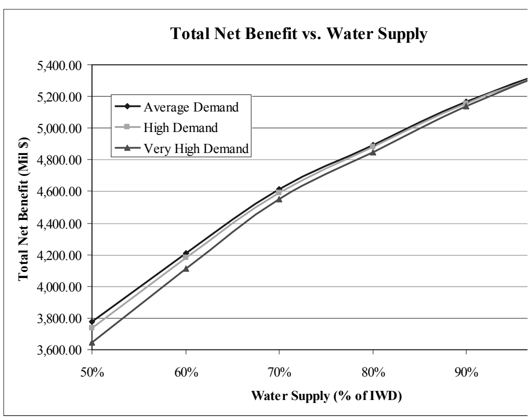


Figure 5. The net benefit for the whole area versus the available water supply from WUA

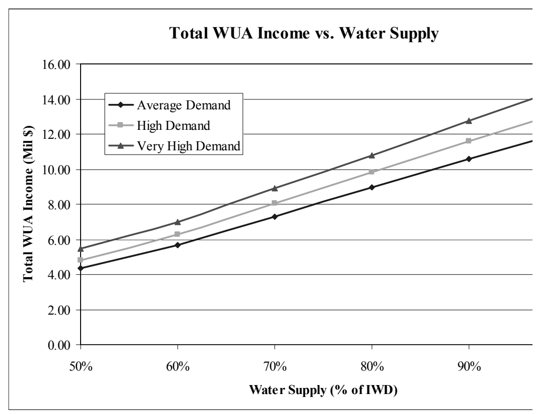


Figure 6. The WUA income for different levels of available water supply from WUA

Figures 5, 6 and 7 report the situation resulting from the first set of model runs. These relate to the optimal allocation of water from WUA. Graphs reported in Figures 8, 9 and 10 represent results from the second set of model runs, which concern the optimal allocation of groundwater over the identified deficit areas. From Figure 5 it can be noticed that the net benefit is rapidly increasing as the water availability increases. Also, the highest increasing rate of net benefit is occurring under the very-high demanding climatic scenario, thus showing that water has a strong effect both on crop yield and on irrigation cost and that this effect has an increasing intensity for increasing water demand conditions. The plot in Figure 6 shows the variation of WUA's income resulting from the water distribution service (sale of irrigation water at increasing unitary prices). Also in this case, the WUA's income increases with increasing levels of water availability. Water is more urgently needed under very-high demanding conditions to avoid any deficit period for crops, which can result in severe yield reduction. For this reason, under very-high demanding conditions farmers are more willing to pay for additional amounts of water in order to avoid any yield loss risk. This can be inferred from the graph, as the rate of income increase varies as the climatic demand scenario becomes more demanding. Similar trends can be observed from the third graph reported in Figure 7, where the actual crop evapotranspiration is plotted versus different levels of water availability. In this case as long as water availability increases also crop evapotranspiration increases by a rate that is different for the three climatic scenarios

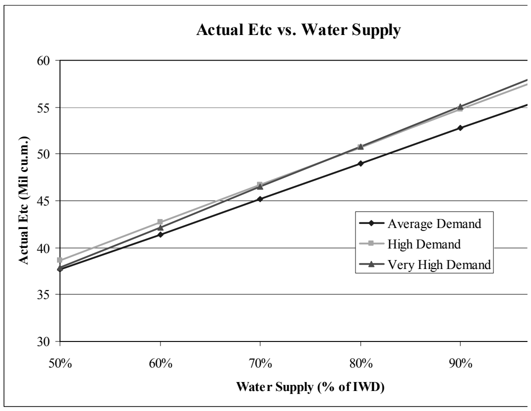


Figure 7. The actual crop evapotranspiration for different levels of water supply WUA

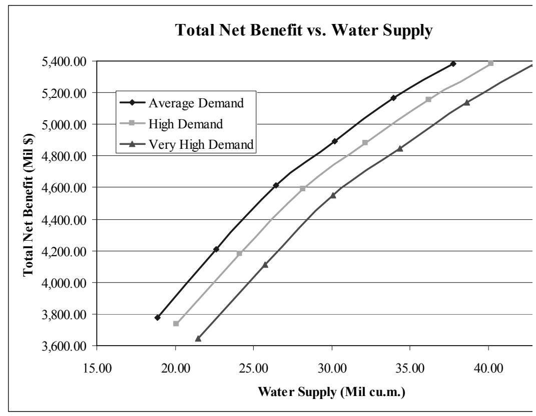


Figure 8. The net benefit versus the available water supply from groundwater

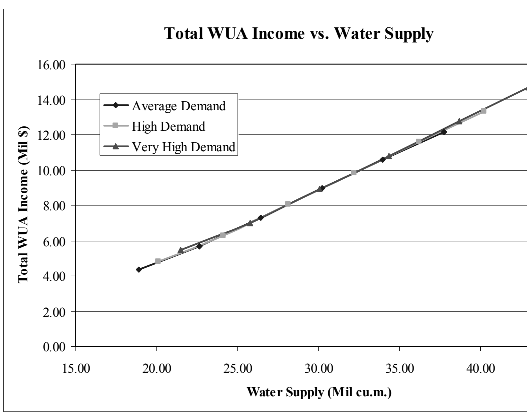


Figure 9. The WUA income for different levels of available water supply from groundwater

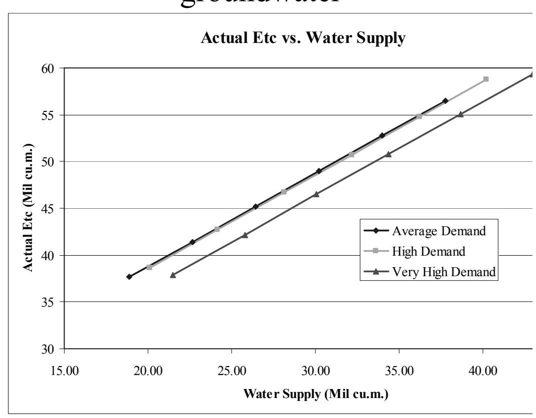


Figure 10. Actual crop evapotranspiration for different levels of water supply from groundwater

In the second set of graphs, net benefit, WUA's income and actual ETc are plotted versus water availability from groundwater aquifers. Similar trends relative to the first set of graphs can be noticed, thus showing that the model is working properly and well representing the simulated conditions.

The optimal solutions found by the model for water allocation were displayed in the GIS environment. In the following sets of figures results from the Very-High Demand scenario are presented. From these, the location of deficits likely occurring under the most critical climatic scenario can be noticed. These deficit areas are also the main targets for allocation of supplemental water to be withdrawn from aquifer.

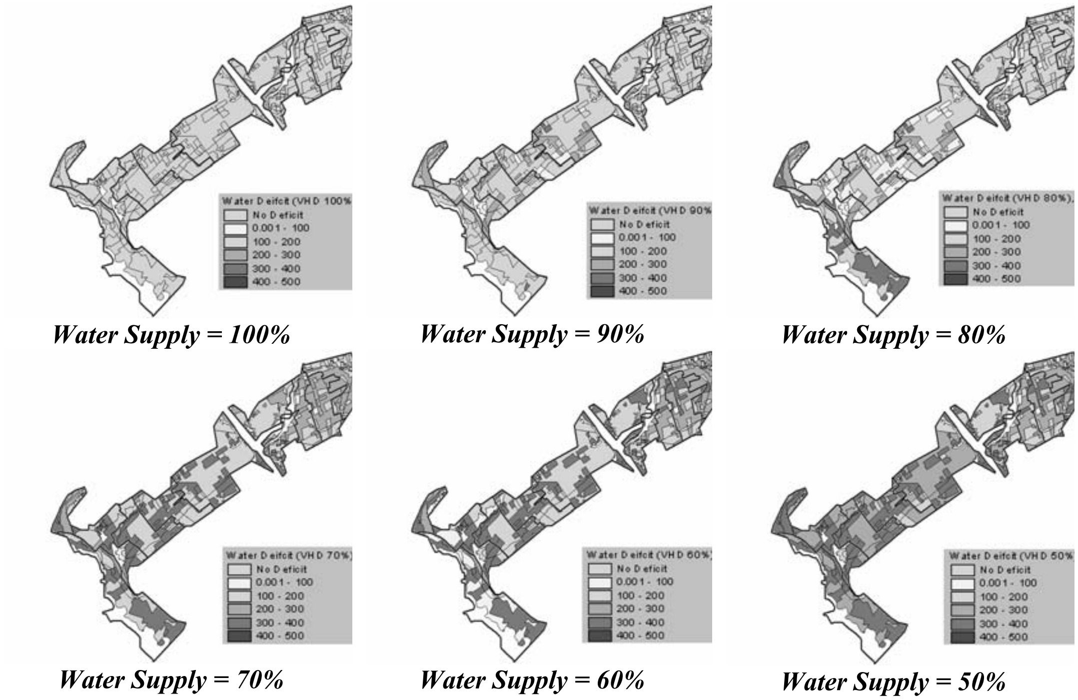


Figure 11. Optimal allocation of water from WUA and resulting deficit areas for the Very-High Demand scenario

CONCLUSION AND RECOMMENDATIONS

The presented model was developed on the site-specific conditions occurring in the study area. Therefore, it can represent the actual situation in irrigated agriculture and also reveal some room for improving water management and economical results both for the WUA and for farmers. To some extent, the model can be useful to understand several issues involved in water management at the large-scale level. The model can also be helpful to district water managers for the following purposes:

a) Evaluating the economical effects of different water management strategies
b) Developing operational plans on a seasonal basis for the irrigation distribution network
c) Developing a plan for conjunctive use of surface and groundwater enabling the economical and environmental sustainability of irrigated agriculture
d) Improving the net benefit for the whole irrigated area and increasing the income of the WUA as related to the irrigation services provided

In order to implement such a model in reality, the water distribution system should be operated on-demand. In this case, in fact, a bottom-up operation will result as farmers would decide when and how much water to take from the distribution network without informing the system managers. Only when the system is operated on-demand, the soil-water balance approach can be applied for quantifying the time-distributed and spatially distributed crop water requirements. The on-demand delivery schedule will also enable to achieve a better efficiency of water use at on-farm level.

As a pre-requisite for this type of operation, an adequate tariff rule based on volumes actually withdrawn by farmers, preferably with increasing rates for increasing volumes should be enforced.

Also, the on-farm delivery points should be equipped with flow meters in order to account for any single withdrawals.

Furthermore, a good communication level should exist between the water management agency and farmers in order to update them frequently about the level of water supply available for the forthcoming time-periods. Finally, good control and supervision over the hydraulic structures and over the aquifer should be implemented in order to enforce the developed plan for conjunctive use of surface and groundwater.

REFERENCES

Consorzio di Bonifica Stornara e Tara - Taranto. (1973). *Verifiche idrauliche per l'inserimento sul canale principale in sinistra Bradano di bacini di compenso per la modulazione della portata.*

Doorembos, J., and Kassam, A.H. (1979). *Yield Response to Water*. FAO Irrigation and Drainage Paper n. 33, Rome, pp 193

Zaccaria, D., (1998). *Reliability criteria for analysis of on-demand irrigation systems*. M.S. Thesis, C.I.H.E.A.M., Bari Istitute, In: Bonifica, 3, 25 - 49.

ASSESSMENT OF THE ENVIRONMENTAL SUSTAINABILITY OF IRRIGATED AGRICULTURE IN A LARGE-SCALE SCHEME — A CASE STUDY

Daniele Zaccaria[1]
Michela Inversi[1]
Nicola Lamaddalena[2]

ABSTRACT

A study was conducted on a large-scale irrigated area located in southern Italy to analyze the cumulative effects of long-term water management practices on soils and aquifers. Assessing the environmental sustainability of irrigation systems operations was the main goal of the present research. This included envisaging feasible changes to "business-as-usual" in the study area with the aim of reducing pressures and of meeting current and future management objectives. The *Determinants-Pressure-State-Impact-Response* methodology suggested by the European Environmental Agency was applied to the case study to analyze cause-effect relationships between driving forces, pressures and potential impacts. Simulations of alternatives in water management and evaluation of resulting consequences were conducted by developing a spatial Decision Support System (DSS) on the study area. This basically involved development and ranking of alternatives by using a commercial software package (DEFINITE DSS).

Evaluation of the most likely resulting consequences was conducted by creating maps of environmental risk by means of two commercial GIS software packages (ArcGIS and IDRISI). The used approach showed its usefulness for achieving better understanding of relevant aspects related to management of irrigation water at regional scale, for designing strategic monitoring programs to be implemented and for envisaging feasible management alternatives on large-scale irrigation systems.

INTRODUCTION

In the arid and semi-arid regions of the Mediterranean irrigation projects, despite their promise as engines of agricultural growth, usually perform far below their potential (Small and Svendsen, 1992). In several cases, unrealistic designs, rigid water delivery schedules and operational problems are among the principal reasons for the poor performance of irrigation systems (Plusquellec et al., 1994).

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[1]Consultants, Department of Irrigation Engineering, International Center for Advanced Mediterranean Agronomic Studies (CIHEAM – IAM Bari), via Ceglie 9 – 70010 Valenzano (BA) – Italy, zaccaria@iamb.it

[2] Head, Department of Irrigation Engineering, International Center for Advanced Mediterranean Agronomic Studies (CIHEAM – IAM Bari), via Ceglie 9 – 70010 Valenzano (BA) – Italy.

In others, system management often fails to respond to the needs of users, in particular to small holders carrying low social and political weight (UNESCO, 2003). In this geographic context irrigation agencies and farmers' associations are continuously asked to improve the efficiency of their irrigation networks and delivery systems by means of improved use of limited water resources (D'urso, 2001). For these reasons, assessment of actual performance and potential improvement of distribution systems are now receiving greater attention, not only from the usual efficiency-type stand-point but also from the environmental perspective. Existing irrigation systems need to be periodically evaluated for their performance achievements relative to current and future objectives. In this view, the proposed study focused on testing a methodology to conduct diagnostic analyses and simulate alternative management scenarios on large-scale pressurized irrigation systems. The approach used proved to work as an analytical basis to address modernization processes with greater accuracy than was done in the past.

OBJECTIVES AND APPROACH

The main objective of the present research was to develop the capability to perform diagnostic analyses on environmental effects resulting from management of irrigation water at regional scale. An analytical approach was proposed for achieving better understanding of major environmental effects of irrigation management to soils and aquifers. The analyses carried out allowed achieving the following specific objectives:

1. Mapping areas of environmental hazards caused by mis-management of water distribution
2. Simulating alternative water management scenarios
3. Evaluating the contribution of each alternative for maintaining environmental and economic sustainability of irrigated agriculture in the area
4. Supporting strategic planning and decision-making by using Decision Support Systems (DSS) and Spatial Decision Support Systems (SDSS)

The rationale followed within the present research is represented in the Figure 1. It involved several methodological steps, which are reported hereafter:

a) Data gathering and generation of basic GIS thematic layers on the study area
b) Processing of GIS thematic maps and standardization of environmental parameters
c) Impact assessment relative to the existing situation and preparation of environmental vulnerability maps
d) Identification of feasible water management alternatives with respect to "business-as-usual" in the study area
e) Setting decision rules and attributing weights for the DSS
f) Ranking the feasible alternatives and setting rules for selection of the most-suitable alternatives
g) Generation of impact maps related to the most-suitable alternatives

BACKGROUND ON THE STUDY AREA

The Sinistra Bradano Irrigation Scheme

The analyses were carried out on the areas served by the “Sinistra Bradano” large-scale irrigation system, which is located in the south-eastern part of the Italian peninsula (Apulia Region). This system covers a total topographic area of 9,500 ha. The physical boundaries of the study area as well as its location, shape, topographic conditions and extent are reported in Figures 2 and 3.

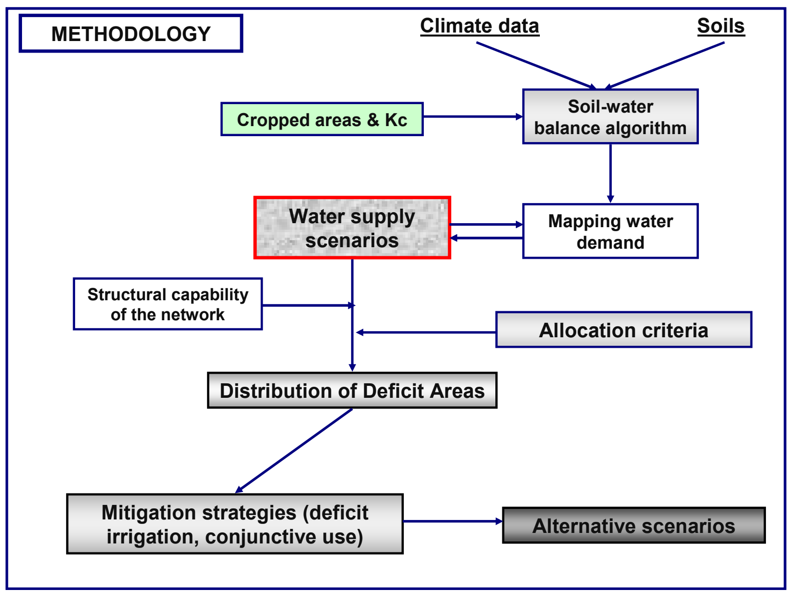


Figure 1. Rationale of the methodology adopted in the study area.

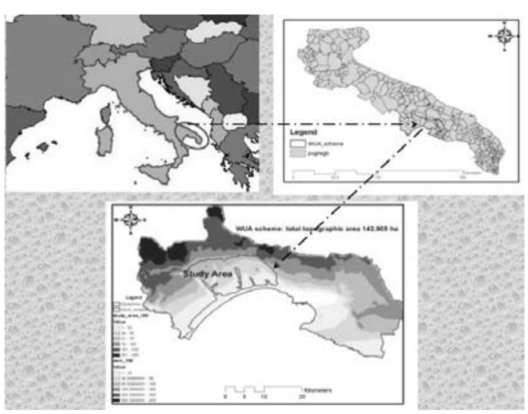


Figure 2. Location and extent of the area of interest

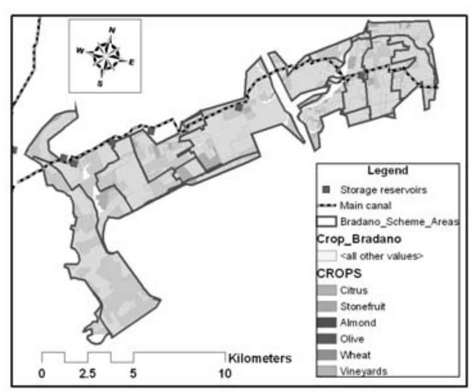


Figure 3. Representation of the “Sinistra Bradano” irrigation scheme

The main irrigated crops are table grapes, citrus, olive and summer vegetables. Most of the farms utilize trickle irrigation as predominant method, while in some limited areas sprinkler irrigation is still utilized for citrus and summer vegetables.

Due to favorable agro-climatic conditions, agriculture in the area is intensive and highly market-oriented. Climate is semi-arid with an average yearly precipitation of about 550 mm, which are poorly distributed along the months. Therefore profitable farming in the area is strongly dependent upon irrigation. The typical irrigation season lasts from the beginning of April to mid November. The hydraulic scheme is composed of a main canal conveying water from a regional dam to four storage and compensation reservoirs, which serve ten irrigation districts. From each of these reservoirs, district pressurized distribution networks originate for delivering irrigation water to the farms. The Figure 3 shows the main features of the irrigation scheme.

The irrigation distribution network is operated by rotation delivery schedule. The usual rotation is based on a 10-day shift. At present, distribution of irrigation water to farms, as reported by many farmers, is too restrictive and not timely matching the actual crop water requirements and farmers' needs. As a result of all the above issues, during the last 10 years a large number of water users started drilling on-farm irrigation wells (nearly 6,000 wells are reported to be existing in the area and most of them are unlicensed). This led to over-pumping from the aquifers, to saline intrusion in groundwater and to an increasing process of salt build-up in the soils. The major environmental concerns in the area can be reported as follows:

1. Climatic conditions, intensive management of agricultural systems and non-optimal allocation of water supplies make *"business-as-usual"* not sustainable in the area on the long run
2. There is high pressure on groundwater resources that resulted in soil degradation and aquifer contamination

Lack of accurate understanding of cause-effect relationships and trends complicate the search for effective solutions. All the above factors are progressively leading the area to environmental unbalances, which likely result in high vulnerability of the study site to further degradations on the medium run, such as salinization of soils and aquifer and potential desertification risk.

THE D.P.S.I.R. MODEL

The **D**eterminants-**P**ressures-**S**tatus-**I**mpacts-**R**esponses Model (D.P.S.I.R.) is a methodology proposed by the European Environmental Agency (EEA) in 1999 and developed on the basis of the Pressure-Status-Responses (PSR) and Determinants-Status-Responses (DSR). The D.P.S.I.R. model represents the scheme utilized by EEA for developing reports on the state of environment in Europe. It enables the description of current environmental problems by identifying the different cause-effect relationships and makes them comparable at the European scale. The model is composed by five stages which allow evaluating the causal process leading to environmental alterations. Besides being a useful approach to frame a problem, the D.P.S.I.R. model represents a sound tool to develop the decision-making process, thus allowing identifying the most promising correction measures to be conducted on a site-specific situation. The comprehensive outlines of the model and of its methodological phases, as applied to the Sinistra Bradano irrigation scheme, are reported in the Figure 4.

The following pressure indicators were identified for the present study area:

1)Salt build-up in the irrigated soils; 2) Salinity level and salinity distribution in aquifer; 3) Magnitudes of water deficits (water withdrawals from aquifer)

As for the State and Impact stages, the following impacts were pointed out for the area served by the Sinistra Bradano irrigation scheme:

- Increase of soil and groundwater salinity
- Decrease of productivity for soils, crops and for agricultural systems
- Soils and water degradation beyond natural recovery capabilities
- Risk of desertification

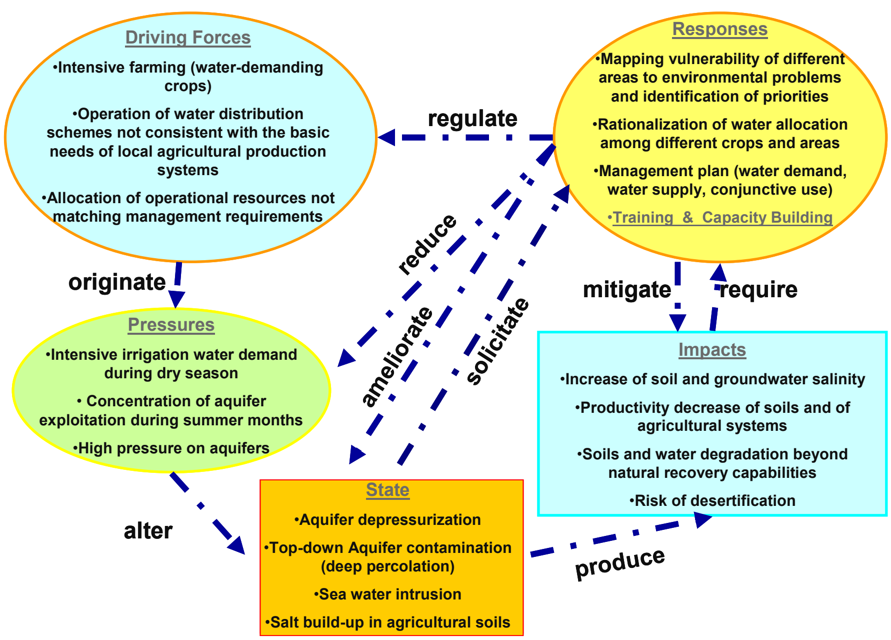


Figure 4. The D.P.S.I.R. model applied to the study area

IMPACT ASSESSMENT, DEVELOPMENT AND EVALUATION OF ALTERNATIVE SCENARIOS

After data collection and processing, the impact assessment relative to the current situation involved the generation of maps of environmental vulnerability over the study area under three different climatic scenarios (Average, High-demanding, Very-high demanding). Those vulnerability maps were produced by combining the following distributed GIS datasets:

1. Standardized maps of pressure exerted to underground aquifer (water pumping from aquifer) under the three specified climatic scenarios
2. Standardized map of salinity distribution in the underground aquifer over the whole study area
3. Standardized map of aquifer recharge over the whole study area

In order to evaluate the spatially-distributed pressure exerted to aquifer, maps of distributed irrigation demand over the study area were first generated under the three different climatic scenarios. Following the indications obtained by the technical staff of the local WUA, a total water supply of 20 Mm^3 was considered. This amount corresponds nearly to 50 % of the total water demand calculated under the three different climatic scenarios. This total available water supply was allocated to the different cropped areas by using an optimization model, which was developed on purpose for the present research. The model basically finds the optimal allocation of limited water supply over the multi-cropped irrigated area. Based upon the model results, distributed maps of water deficit were generated. These water deficit situations refer to the share of water deliverable to cropped areas based upon results from the optimization model and upon the total available water supply. As an example, the maps of water deficit under the very-high demand climatic situations are reported in Figure 5. Given that water deficit situations imply pumping from the aquifer the necessary volumes for full satisfaction of crop irrigation requirements, the water deficit maps were considered as distributed maps of potential water withdrawals from aquifer. These water withdrawals correspond to the amounts of water that farmers are likely to be pumping from aquifer during the irrigation season in the different irrigation districts all over the cropped areas.

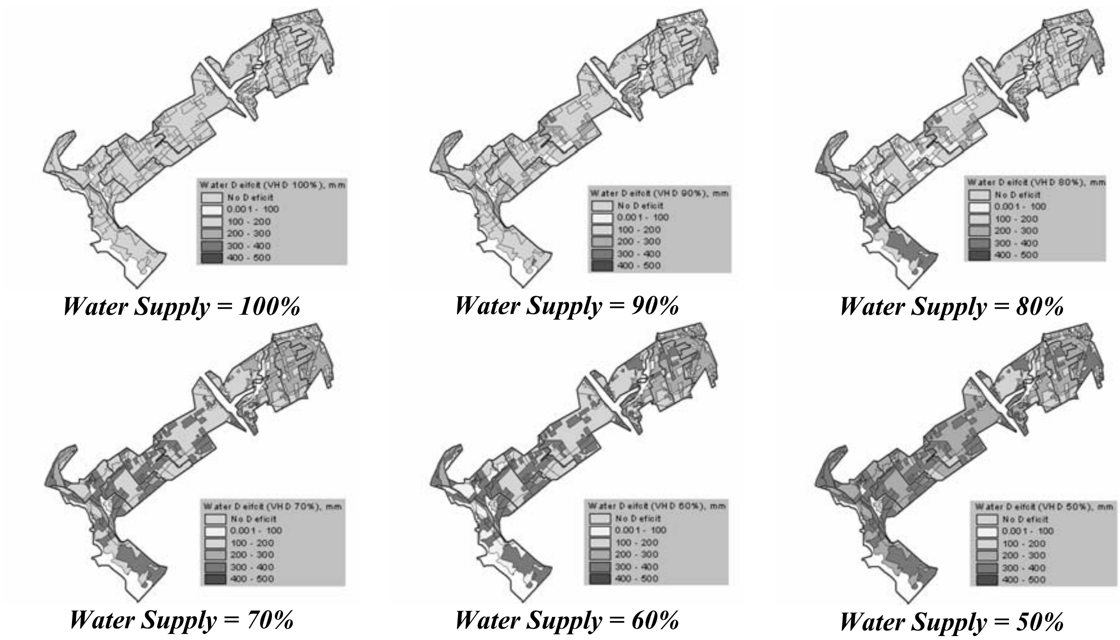


Figure 5. Optimal allocation of water from WUA and resulting deficit areas for the Very-High Demand scenario

DEVELOPMENT OF THE SPATIAL DSS

The maps of potential water pumping, salinity distribution and aquifer recharge were generated using ArcView and ArcGIS software packages and then imported into the commercial software IDRISI, which is a Spatial DSS working on geo-referenced files.

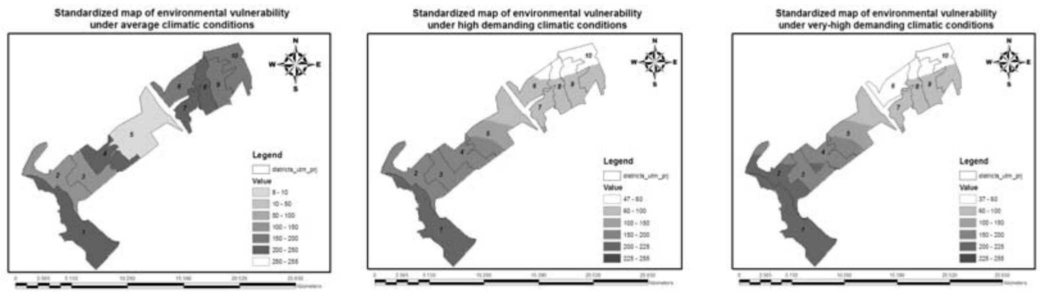
The standardization procedure was performed in IDRISI in order to homogenize maps having different units and to combine them into environmental vulnerability maps.

The standardized maps of pressure, salinity and aquifer recharge were combined into IDRISI by using *Decision Support* functionality calling for *Multi Criteria Evaluation* (MCE) through a *Weighted Linear Combination*, thus attributing the weights reported in the following Table 1 to the different factors.

Table 1. Weights allocation to the different factors used in the Multi Criteria Evaluation to generate maps of environmental vulnerability for the study area

Factor	Factor	Weight
1	Pressure exerted to aquifer	0.3
2	Aquifer salinity	0.5
3	Aquifer recharge	0.2

Following the above-described approach, three different maps of environmental vulnerability, one for each climatic scenario, were generated and are presented in the Figures 6.



Average climatic conditions | *High-demanding climatic conditions* | *Very-high-demanding conditions*

Figure 6. Standardized maps of environmental vulnerability under different conditions

Afterwards, several alternative scenarios with respect to the "business-as-usual" (Zero-Alternative) were developed with the aim of reducing the pressure over the aquifer by means of a better water distribution to farms. These water management alternatives were generated and defined by using the DEFINITE DSS software package (Janssen et al., 2003) and are reported in the Table 2. Once the feasible water management alternatives were defined, the decision rules (effects) and attribution of weights for the Multi Criteria Analysis were also determined as presented in the following Table 3. The subsequent step to the definition of effects and attribution of weights was the determination of decision-making criteria. Two separate simulations of Multi Criteria Analysis (MCA) were run, the first one mainly addressed at achieving *Environmental Sustainability* in the area, whereas the other was mostly oriented to achieving *Economic Feasibility*. The two simulations are based upon different decision-making criteria, which were developed by assessing weights effects through pair-wise comparisons between the different effects, taken two at a time. Assessing the relative importance weight of each effect with respect to the other ones allowed setting the decision-rule on which to base the alternative ranking. The eight alternatives, including the "business-as-usual" (Zero Alternative) were ranked applying the Multi Criteria Analysis (MCA) in the DEFINITE software package.

Table 2. Water management alternatives generated in DEFINITE DSS for the area

Alternative	Description
1	Modernization of the irrigation distribution network to allow for on-demand delivery schedule
2	Optimal combination of supplementary water from other irrigation schemes, rehabilitation and modernization of the irrigation distribution network
3	Combination of centralized water pumping from aquifer and modernization of irrigation distribution network
4	Combination of conveyance of supplementary water from other water schemes and modernization of irrigation distribution network
5	Business as usual (Zero Alternative)
6	Optimal combination of centralized water pumping from aquifer and rehab. and modernization of the irrigation distribution network
7	Combination of rehabilitation and modernization of the irrigation distribution network
8	Rehabilitation of the irrigation distribution network

Table 3. Decision rules and units to be used in the Multi Criteria Analysis for the study area

Effect	Effect description	Unit
1	Overall monetary cost for physical works necessary to implement the alternative	(----/++++)
2	Time necessary for implementing the alternative	(----/++++)
3	Efficacy in reducing water deficit	(%)
4	Required engineering & management skills and capacity-building for implementing the alternative	(----/++++)
5	Efficacy in reducing pressure to aquifer	(%)

RESULTS AND DISCUSSION

The results are presented in the Figures from 7 to 12. These results show that under the High-Environmental Sustainability decision scenario the most advisable alternative is the optimal combination of supplementary water from other irrigation schemes, rehabilitation and modernization of the irrigation distribution network (Alternative 2). Alternative 4 (Combination of conveyance of supplementary water from other water schemes and modernization of irrigation distribution network) is ranked as second-best, right after the Alternative 2. The Business-as-usual alternative, which corresponds to the actual asset in the study area, is ranked as last, due to the fact that its environmental sustainability is very poor. Under the High-Economic Feasibility scenario, ranking of alternatives is almost opposite, as the main purpose here was to find fast and cheap alternative solutions to the current situation. Therefore, cost and time necessary for implementing alternatives are in this case the most relevant factors in the decision-making.

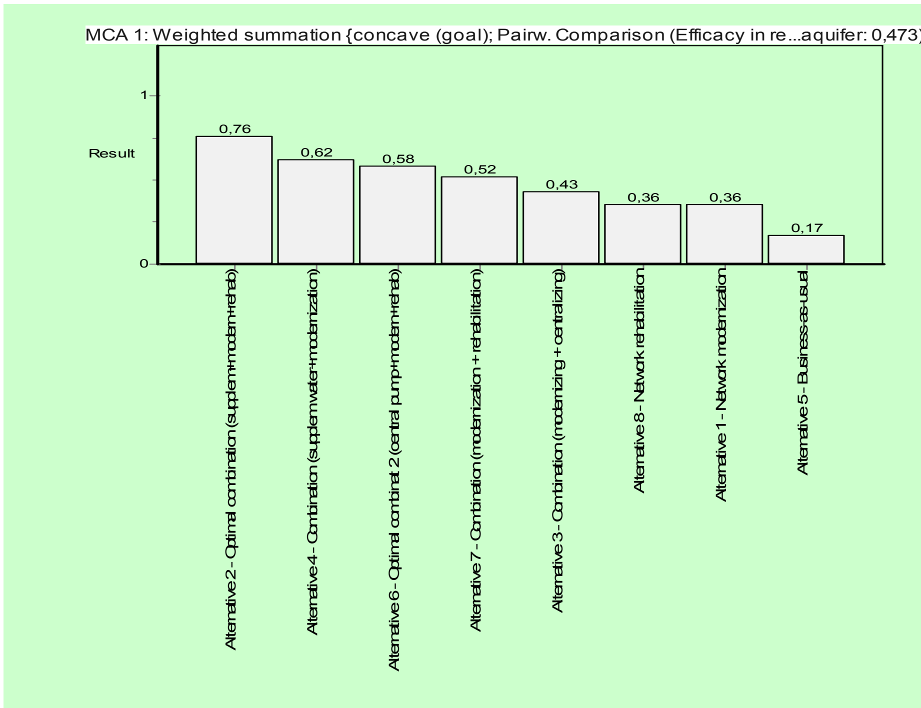


Figure 7. Ranking of alternatives from the MCA under High-Environmental Sustainability

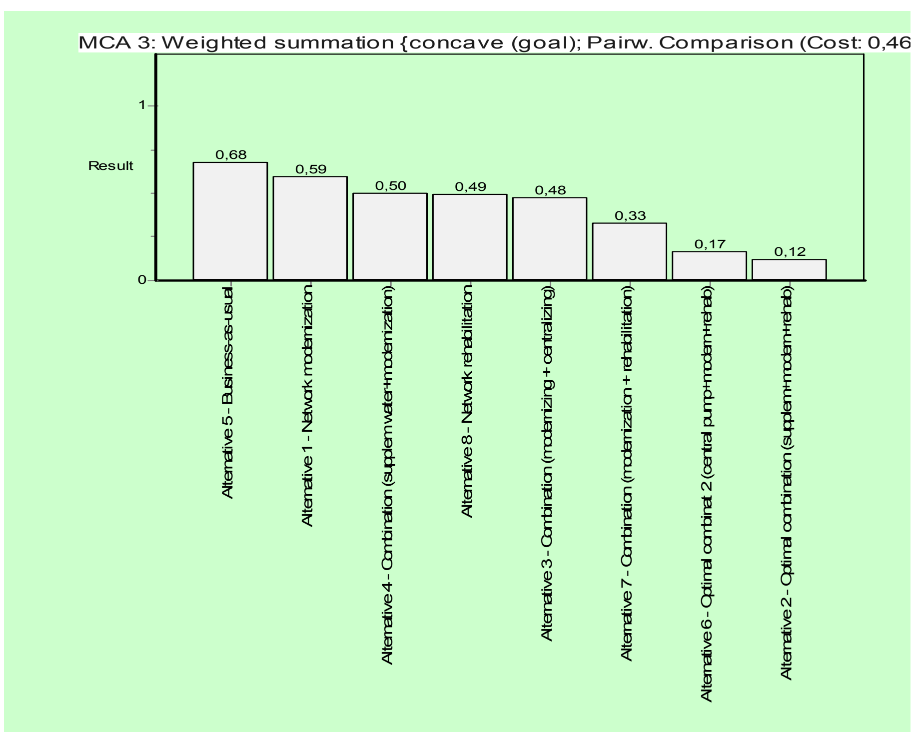


Figure 8. Ranking of alternative from the MCA under High-Economic Feasibility

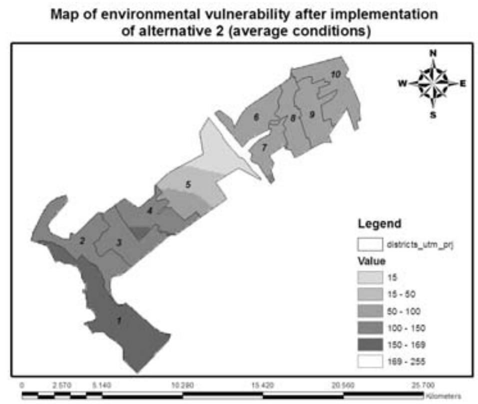


Figure 9. Map of environmental vulnerability after implementing the Alternative 2

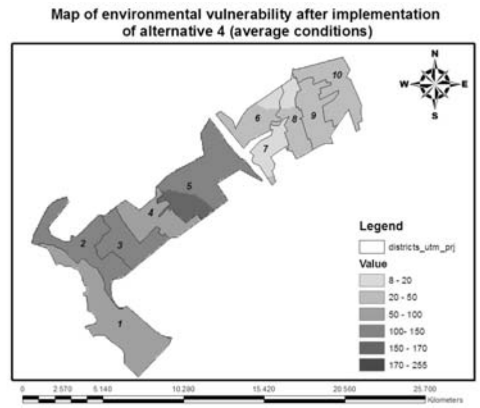


Figure 10. Map of environmental vulnerability after implementing Alternative 4

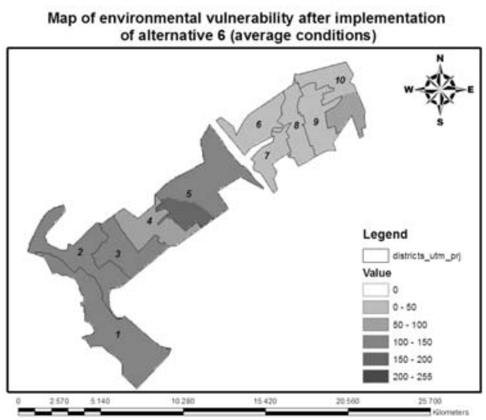


Figure 11. Map of environmental vulnerability after implementing Alternative 6

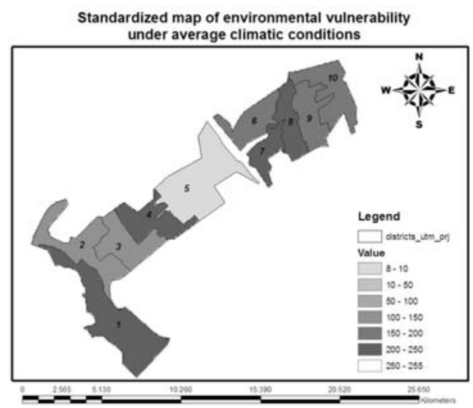


Figure 12. Map of environmental vulnerability after implementing Alternative 5

GENERATION OF IMPACT MAPS OF THE ALTERNATIVES

The impact on environment resulting from the different proposed alternatives was evaluated by considering the contribution of each alternative to reduce the pressure exerted on the aquifer and to decrease the water deficit. Both criteria are inter-related and therefore each water management solution will result in a different level of pressure exerted over the aquifer, which in turn will determine a mitigated environmental vulnerability with respect to the Zero Alternative (business-as-usual). The complete impact attribution of the different alternatives, necessary for running the MCA, can be observed from the Table 5.

Table 5. Complete impact attribution of the different alternatives

Effect	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8
Cost	+	++++	++	++	0	++++	+++	++
Time for implementation	+	++++	++	++	0	+++	+++	++
Efficacy in reducing water deficit (%)	30	100	70	70	0	100	60	30
Required capacity building	++	++++	+++	+++	0	++++	+++	+
Efficacy in reducing pressure to aquifer (%)	30	100	30	70	0	60	60	30

CONCLUSIONS AND RECOMMENDATIONS

The results from the development of a Decision Support System on the area served by the Sinistra Bradano irrigation scheme show that sound decision-making involves the availability of accurate datasets and the consideration of a number of economic and environmental aspects from the standpoints of different stakeholders. Such complex problems can be framed by using Spatial Decision Support tools and feasible alternative solutions can be more addressed to environmental sustainability or to economic feasibility. In order to improve the whole decision process, adequate decision guidelines could be elaborated and suggested within a Water Management Plan to be implemented for each large-scale irrigated area.

REFERENCES

D'Urso, G. (2001). *Simulation and management of on-demand irrigation systems*. Ph.D. Dissertation, Wageningen University, The Netherlands, pp 174

EEA, (1999). Groundwater quality and quantity in Europe, European Environmental Agency –Copenhagen

Janssen R., van Herwijnen M., Beinat E.. DEFINITE 3.0 case studies and user manual. Institute for Environmental Studies, Vrije Universiteit Amsterdam, The Netherlands. Report number R-03/03, 2003.

Plusquellec, H.L. C.M. Burt & H.W. Wolter. 1994. Modern water control in irrigation. Concepts, issues, and applications. World Bank Technical Paper 246. Irrigation and Drainage series. World Bank.

Small, L.E., Svendsen, M. 1992. A framework for assessing irrigation performance. Working Papers on Irrigation Performance No. 1. Washinghton, D.C., International Food Policy Research Institute.

United Nations (UNESCO, 2003). World Water Development Report, Water for people water for life. 573