Challenges Facing Irrigation and Drainage in the New Millennium

Volume II, Poster Session

Meeting Human and Environmental Needs through Sustainability, Rehabilitation and Modernization

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Preface

These Proceedings include the papers presented during the **International Conference on the Challenges Facing Irrigation and Drainage in the New Millennium**, sponsored by the U.S. Committee on Irrigation and Drainage. The Conference, held June 20-24, 2000, in Fort Collins, Colorado, brought together water resources professionals from around the world to discuss issues relating to the Conference theme, *Meeting Human and Environmental Needs through Sustainability, Rehabilitation and Modernization.*

Success in agricultural productivity over recent decades has been described as not so much a "green revolution" as a "blue revolution"— the fruit derived from controlled water application, made possible by vast irrigation systems. Ironically, at a time when more and more reliance is being placed on the high yields derived from irrigation, the management, resources and infrastructure of irrigated agriculture are vulnerable to mounting challenges and problems. The goal of the Conference was to provide a forum for thoughtful discourse on how to keep irrigation thriving in its service to human need, while sustaining its resource base and promoting beneficial interaction with its natural and economic environment.

Conference presentations included new developments in irrigation and drainage research, as well as the latest innovations and technological advances practiced both in the United States and internationally. Case studies highlighted the experiences and lessons learned during recent years. The Proceedings contain invaluable information for water resources professionals around the world who strive to improve the science and technique of irrigation and drainage, for the benefit of the global population.

Papers included in the Proceedings were accepted in response to a call for papers and were peer-reviewed prior to preparation of the final papers by the authors. Two volumes comprise the Proceedings: Volume I includes papers prepared for oral presentation during the Conference Technical Sessions and Volume II features papers presented during the Poster Session. The authors, from 16 countries, are experts from academia; federal, state and local government agencies; water districts and the private sector.

The 34 papers in Volume I were presented during five Technical Sessions:

- Operation and Maintenance
- Cross Boundary Issues
- Drainage and Water Quality
- Organization
- Water Management

Volume II of the Proceedings includes the 35 papers presented in the Conference Poster Session.

The U.S. Committee on Irrigation and Drainage, and the Conference officers express gratitude to the authors, session moderators and participants for their contributions.

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Contents — Volume II

Poster Session

CONTROLLED DRAINAGE STRATEGIES TO SAVE WATER IN SEMI-ARID AGRICULTURAL AREAS SUCH AS THE NILE DELTA, EGYPT

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ABSTRACT

Current global population growth rates require an increase in agricultural food production of about 40-50% over the next thirty to forty years, in order to maintain present levels of food intake. To meet the target, irrigated agriculture must play a vital role, in fact the FAO estimates that 60% of future gains will have to come from irrigation.

The practice of controlling drainage involves the extension of on-farm water management to include drainage management. With the integration of irrigation and drainage management, the water balance can be managed to reduce excess water losses and increase irrigation efficiencies.

Controlled drainage is relatively new and there are many theoretical and practical issues to be addressed. The technique involves maintaining high water table in the soil profile for extended periods of time, requiring careful management to ensure that crop growth is not affected by anaerobic conditions.

A fieldwork programme has been investigated to test controlled drainage in the Nile Delta, where water resources are stretched to the limit. Water saving is essential in the next 20 years. Pressures from the fixed Nile water allocation, population growth, industry and other sectors and the horizontal expansion programme mean that this need is urgent.

One crop season has been completed at a site in the Western Nile Delta using simple control devices in the subsurface drainage system. This paper discusses the potential benefits of controlled drainage to save water in agricultural areas such as the Nile Delta, and presents findings from the first crop season.

INTRODUCTION

Current global population growth rates require an increase in agricultural food production of about 40-50% over the next thirty to forty years, in order to maintain present levels of food intake. To meet the target, irrigated agriculture

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must play a vital role; in fact the FAO estimates that 60% of future gains will have to come from irrigation. For this to happen two major constraints must be overcome – irrigated agriculture must use water more efficiently and quality of water and soil resources must be maintained.

Irrigated agriculture is a major global water user. Two thirds of all water abstracted from rivers and underground aquifers are used for irrigation, in the developing world the proportion is even higher. Water is typically used inefficiently with wastage of water supplies, transfer of pollutants to groundwater, and waterlogging and salinization of the root-zone.

In semi-arid areas there is often the need to supply extra water for salt-leaching purposes, which leads to a consistent volume of water percolating below the crop root zone and downwards until it meets the local water table. Over many years this over-irrigation has caused the water table to rise close to the crop root zone and the soil surface, necessitating the need for water table control by artificial drainage.

Artificial drainage for water table control commonly takes the form of open ditches at field edges and subsurface drains laid horizontally across fields at a depth of 1-2m and spacing of 20-80 m. In the majority of cases, drainage systems are over designed (it is often policy to design for the crop most sensitive to waterlogging) and irrigation applications are inefficient. The combined effect is that drainage rates often exceed evapotranspirative demands and the drainage system removes water from the soil, so it is no longer available to meet ET demands.

Loss of excess water through drainage is often a major component of inefficiency in irrigation systems. Controlled drainage is a practice that allows farmers to control drainage outflows, storing water in the soil profile for use by the crop and reducing losses from the system. Water management at the field-level has traditionally been thought of only as irrigation management. When irrigation management is integrated with drainage management this opens up new opportunities for water saving, increased insurance against crop losses due to water shortage, and possible water quality benefits.

This paper describes initial findings of an ongoing project to develop integrated irrigation and drainage management strategies incorporating controlled drainage, to save water and protect water resources in semi-arid regions such as the Nile Delta. The project (DFID KAR contract R7133) is being carried out by the Water Management Department of HR Wallingford in collaboration with the Drainage Research Institute of the National Water Research Centre, Egypt.

CONTROLLED DRAINAGE

Drainage systems in irrigated agricultural areas are traditionally designed solely to maintain agricultural productivity by controlling (saline) high water tables. Systems are designed to remove water rapidly from the soil profile. With conventional farming practice there is irrigation management, but no drainage management, and large volumes of water leave the soil profile through the subsurface drainage system. This constitutes a major factor in the water loss from many agricultural areas. Water quality protection and water saving aspects are not addressed. As a result (Grismer and Tod, 1991) significant root zone percolation and solute load can bypass drains and move to the deep aquifer for groundwater deterioration, and useful water is often lost from the soil profile without the crop having the chance to use it.

The practice of controlling drainage involves the extension of on-farm water management to include drainage management. With the integration of irrigation and drainage management, the water balance can be managed to reduce excess water losses and increase irrigation efficiencies.

With controlled drainage the farmer is able to control the amount of water leaving the land. A weir (or other control structure) or blocking device is used to control drainage outflows. Gravity or pumped drainage occurs only after the water level in the drainage ditch, pump sump or water table in the field has risen to a level where drainage should be provided to prevent crop damage or provide salt leaching. To attain this, drainage is stopped or restricted by some device when the water table or ditch level drops to a certain level. When the water table rises above this point (by rainfall or irrigation) free drainage occurs again.

Controlled drainage is relatively new and there are many theoretical and practical issues to be addressed. The technique involves maintaining high water tables in the soil profile for extended periods of time, requiring careful management to ensure that crop growth is not affected by anaerobic conditions.

To prevent accumulation of solutes (particularly salts) in the root zone it is necessary to maintain leaching processes. With proper management, controlled drainage techniques should improve efficiency of solute removal in drain flow and protect the crop root zone and groundwater resources.

There has been research into controlled drainage, primarily in humid areas, and it has been adopted in several locations. Countries include USA, Canada, Bulgaria, Poland, Finland and Holland. The main benefits (depending on location) have been identified as:

- Yield increases.
- Water and energy savings.
- Water quality protection

Most of the work to date has been in humid areas, but controlled drainage is likely to be beneficial in many arid and semi-arid regions of the world, where water tables are high. Potential areas of application include Egypt, Pakistan and India.

Controlled drainage is suited to areas with a high water table. Blocking of drains allows the irrigation water to remain in the field close to the crop root zone for a sustained period of time. This water is then fully available to the crop.

In theory, if the amount of water applied by irrigation is equal to the crop water requirements then water could be applied indefinitely and the water table level would remain stable. However, in semi-arid areas a leaching requirement is necessary to wash the salts out of the root zone (Manguerra and Garcia 1997). This extra water means that the water table will rise steadily over a couple of growing seasons. A period of drainage is therefore required to flush out the excess water and salts. According to predictions in California, if the drains are not opened for consecutive growing seasons, the crop will be subjected to excessive waterlogging during the third season (Manguerra and Garcia 1996).

The work concluded (Evans *et al*, 1996) that when controlled drainage was applied all year it reduced total outflow by approximately 30 percent compared to conventional systems, although outflows varied widely depending on soil type, rainfall, type of drainage system and management.

POTENTIAL AND CONSTRAINTS FOR APPLICATION OF CONTROLLED DRAINAGE IN EGYPT

Egypt's existence depends on the River Nile, the largest renewable source of fresh water in northern Africa. It provides, almost exclusively, the source of water for agriculture, industrial and domestic use in this extremely arid land, and is a major fishery throughout its length. The agricultural sector is the largest water consumer, using about 85% of Egypt's surface water resources at present. A network of about 30,000km of irrigation canals and 17,500km of drainage channels serve the estimated 7.4 million feddans (1 feddan = 4200 m^2) of irrigated land in Egypt.

The Government of Egypt has embarked on an ambitious horizontal expansion program to increase the total irrigated land area using the fixed water allocation of 55.5 bcm/yr. Major projects include:

- Toshka Project – designed to develop 0.5 million feddans of desert land in Upper Egypt for agricultural production in the next 10-20 years taking up to 5 bcm/yr of river Nile flow from Lake Nasser.

- Salam Canal Project – to divert 2 bcm/yr drain water from the Bahr Hadus and Lower Serw drain basins in the Eastern Delta for 200,000 feddans irrigated area in west Suez and 400,000 feddans reclamation in Sinai. Irrigation has started in west Suez and reclamation will commence shortly in Sinai.

- Umoum Drain Project – to reuse 1 bcm/yr of drain water from Umoum drain basin in the Western Delta for 0.5 million feddans irrigation in Nubaria. Physical works are underway.

These projects will have major impact on the water balance of the Nile Delta. Water savings are imperative. Major strategies adopted within the country include reusing drain water for irrigation, and improving irrigation management in the Delta.

Agricultural areas of the Nile Delta have three attributes that immediately suggest controlled drainage would be appropriate and beneficial:

- High water table in many locations.
- Extensive subsurface drainage system.
- High drainage flows – constituting a major water loss at field scale.

In fact there have been (and still are) studies into controlled drainage in Egypt, but these have only considered controlled drainage under **rice**, and not addressed potential benefits under dry-foot crops.

Two major studies were carried out by DRI (rice seasons 1996 and 1997) in farmers' fields in the Balaktar area of the Western Delta, east of Damanhur City in Beheira Governerate (DRI, 97 and DRI, 98). These studies demonstrated the significant potential for controlled drainage (with modified drainage design) to save water under rice field. This programme is ongoing, with efforts focusing on mechanisms to implement the approach on a large-scale in rice areas. Although work to date on controlled drainage in Egypt has identified major potential savings in water under rice, no work has been done to assess possible benefits under other crops.

SIMULATION MODEL

The water management simulation model DRAINMOD-S (Kandil et al, 1992), a modified version of the original DRAINMOD (Skaggs, 1978) which is based on a water balance in the soil profile, was chosen for this study. The model was developed in Fortran for the design and evaluation of multi-component water management systems on shallow watertable soils in humid regions, it has subsequently been extended and successfully applied in semi-arid areas (Kandil, et al 1995 and Gupta et al, 1993). DRAINMOD-S allows salt concentrations in the soil profile and drainage water to be calculated throughout the season.

The model is a field water balance model developed and refined over many years. It computes daily water and salt balance and water table depths, and seasonal crop yields. It allows simulation of conventional and controlled drainage using weirs, and has been applied and verified in semi-arid regions including the Nile Delta.

Simulation of Water Management Strategies

The DRAINMOD-S model was used to develop controlled drainage strategies for 6 scenarios of water availability – ranging from the current water use scenario, through scenarios of summer and winter water shortage to a year-round reduction in water available for irrigation. These results are summarised in Table 1 below:

Table 1. Irrigation Amounts (mm) Applied under the Demonstration Scenarios

	Normal (current situation)	Summer Water Shortage	Winter Water Shortage	Increased Summer Water Shortage	Increased Winter Water Shortage	Year-Round Water Shortage
Cotton	779.3	701.8	779.3	612.4	779.3	612.4
Wheat	559.6	559.6	511.8	559.6	429	429
Maize	750.6	662.7	750.6	607.3	750.6	607.3
Berseem	365.8	365.8	224.1	365.8	142.6	142.6
Rotation Total (% water use)	2455.3 (100%)	2290 (93%)	2265.8 (92%)	2145 (87%)	2101.5 (86%)	1791.3 (73%)

The input data for the DRAINMOD-S model for soil, climatic, irrigation, drainage design and crop data are collected from the Maruit site in the Western Nile Delta.

For each water use scenario, the tool was used to assess water and salt balance, crop response and farmer costs for conventional irrigation and drainage operation, and eight to ten proposed controlled drainage designs. The controlled drainage strategies were based on setting different weir depths during crop seasons as outlined in Table 2 below.

Table 2. Controlled Drainage Strategies

Drainage Strategy	Controlled Drainage Crops	Months CD applied	Weir depth
CONV	None	None	None
CD1	Cotton	April – Oct	60cm
CD2	Cotton	April – Oct	90cm
CD3	Wheat	Oct – April	60cm
CD4	Wheat	Oct – April	90cm
CD5	Maize	May – Sept	60cm
CD6	Maize	May – Sept	90cm
CD7	Berseem	Oct – Feb	60cm
CD8	Berseem	Oct – Feb	90cm
CD9	Combination	Varies	Varies
CD10	Combination	Varies	Varies

A total of 63 cases (6 water-use scenarios, with conventional irrigation and drainage, and eight to ten proposed controlled drainage designs) were assessed over a 20-year period, using a 2-yearly crop rotation of cotton, wheat, maize and berseem. This crop rotation is considered one of the most common crop rotations in the Nile Delta.

A predictive design tool (Microsoft Excel with Visual Basic programme) was thus used to identify controlled drainage strategies that satisfied the following criteria:

- Reduced irrigation water use (compared to current irrigation applications under conventional irrigation and drainage).
- Strategies are sustainable. This was defined as no overall increase in soil salinity levels over the 20-year simulation period, and no increase in drain flow.
- Crop yields should be maintained (compared to conventional option with current water use). Average seasonal crop yields to be greater than 95%, and no single crop season with below 90% crop yield.
- Farmer costs should be reduced or stay the same.

The results are summarised below in Table 3.

Table 3. Water Saving Controlled Drainage (CD) Strategies

Strategy	Description	Water Saving
3CD3	CD during wheat season Oct-April, weir set at 60cm	8%
3CD9	CD during wheat season Oct-April, weir set at 60cm AND CD during cotton season April-Oct, weir set at 90cm	8%
5CD9	CD during berseem season Oct-Feb, weir set at 90cm AND CD during wheat season Oct-April, weir set at 60cm	14%
5CD10	CD during berseem season Oct-Feb, weir set at 90cm AND CD during wheat season Oct-April, weir set at 60cm AND CD during cotton season April- Oct, weir set at 90cm	14%

Four controlled drainage designs satisfied the criteria, offering water savings of 8 and 14% on an annual basis. All four strategies allowed reduced irrigation applications during the winter months, when wheat and berseem were grown.

The most beneficial controlled drainage design (of the ones tested) was found to be a weir setting of 60cm during the wheat crop season from October to April. This option featured in all four beneficial strategies. The "best" design (high water saving, highest crop yields) was found to be a combination of controlled drainage in three crop seasons – weir depths of 90cm during berseem, 60cm during wheat and 90cm during cotton seasons.

FIELD APPLICATION OF CONTROLLED DRAINAGE

Experimental Site

The field study is currently being carrying out at the Maruit experimental station, which is located about 35 km south of Alexandria City. The soil of the site is classified as clay loam to sandy clay loam. The measured hydraulic conductivity by using the auger hole method is about 2 m/day. The soil is considered to be representative for the soil of western Delta of Egypt.

The area is served by a new subsurface drainage system installed in May 1999. The collector drains (PVC corrugated plastic pipe) have been installed at about 1.5 m depth and the lateral drains (PVC pipe covered by synthetic envelope materials) have been installed at depth 1.2 m with an average spacing about 32 m. As shown in Fig. 1, a water table control device has been designed from special PVC pipe, consisting of three parts. The first part is a horizontal PVC pipe 75-mm diameter connected to the lateral drain in the manhole at the same level as the lateral drain and closed at the end by PVC closed device. The second part is a riser with multi-heights depending on the minimum water table depth and connected vertically with the first connection. The third part is another horizontal PVC pipe 75-mm diameter connected with the riser as a lateral drain at the desired minimum water table depth. This is designed to restrict the drain flow by plugging the original drain outlet. No drainage outflow will occur until the water table level exceeds the desired minimum water table level.

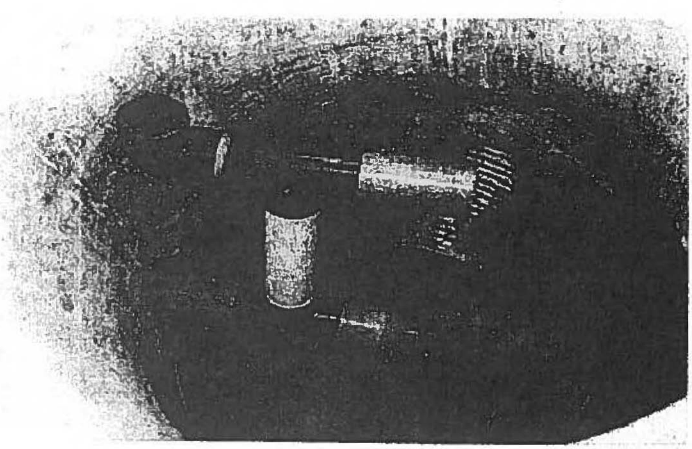

Fig 1. Water table control device

One advantage of this control device is that different riser pipe with different heights can replace the existing riser depending on the root depth and the designed minimum water table depth. No drainage flow will occur until the water table reaches the level of the riser pipe and it is very easy to apply the conventional drainage for leaching by opening the closed device.

Two water table management methods have been applied in the site: the conventional subsurface drainage and the controlled drainage. Each treatment has been applied in an area of about 3 fed (just over 1 hectare) and served by four lateral drains.

The controlled drainage was applied at 60-cm water table depth during the maize cropping season 99. During the crop season the two treatments were applied with the same irrigation water application, the same agricultural management, the same fertilizer application, and the same boundary condition

Data Collection

Soil salinity was determined at the beginning and at the end of the season by taking soil samples at 30-cm interval to 1.2-m depth in different locations of the applied treatments. The ground water depth was measured daily at 32 observation wells covering the study area. The salinity of ground water was measured two times per week at the observation wells by using the EC salinity probe. The soil potential was measured daily at 6 depths in each treatment by using tensiometer profile groups. The rate of drain flow was measured by using bucket and stopwatch at each of the monitored lateral drain outlets. The amount of applied irrigation water for each treatment and also salinity was also measured. Irrigation water, ground water and drainage water samples were collected before and after fertilizer application and analysed for Nitrate –N. Also soil samples were taken at each treatment from 4 depths before each fertilizer application for Nitrate-N analysis The crop yield at harvest time was measured at each treatment by estimating the yield from a specified area.

RESULTS

The results of the summer season of 1999 are as follows:

Ground Water Depths

As shown in Fig. 2 the application of water table control device succeed in raising the water table to the desired level (60-cm) during irrigation time. However the water table was not able to remain at this level due to lateral seepage out of the plots. The main reasons for the lateral seepage are that the permeability of the soil was high (2m/day) and the plot size is small.

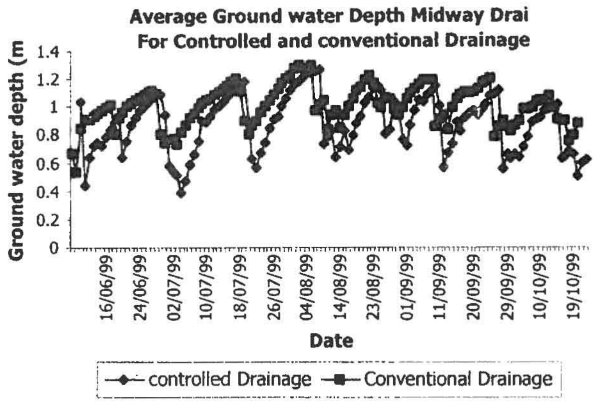

Fig. 2. Ground water depths during summer season 99

Drain Discharge:

The drain discharges for the conventional subsurface drainage and the controlled drainage during the maize season 99 is shown in Fig. 3.

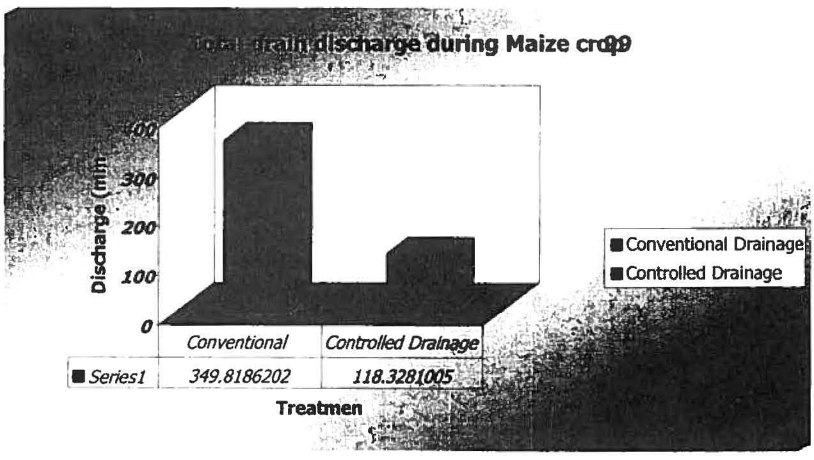

Fig. 3. Total drain discharge during maize crop season 99

The total drain discharge for controlled drainage was about 119 mm and the total drain discharge for the conventional subsurface drainage system was about 350 mm. However, because of high soil hydraulic conductivity, small plot size and low water table in neighboring fields, most of the water in the controlled plot not leaving the field via the subsurface drainage system is leaving the field via lateral seepage. In areas without lateral seepage problems (or in much larger controlled drainage areas), it is likely that this reduction in drainage flow would constitute a significant water saving.

Maize Crop Yield:

The maize crop yield during summer season 99 is shown in Fig. 4. The controlled

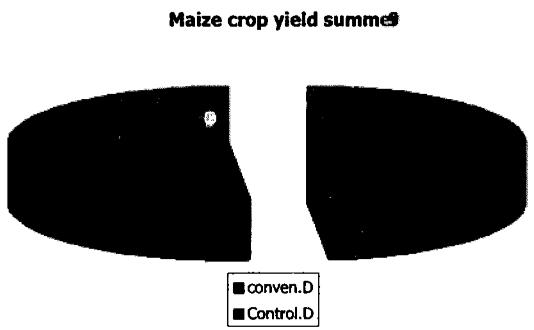

Fig. 4. Maize Crop Yield Summer 99

drainage application gave a crop yield 6.9% higher than the conventional subsurface drainage system. This may be attributed to the improvement of the soil moisture conditions in the root zone area by allowing the water table to raise to a higher level under controlled drainage.

CONCLUSIONS AND RECOMMENDATIONS

- Controlled drainage has been proposed as a water saving management technique for irrigated areas with high water tables and subsurface drainage systems. The technique has been applied (mainly) in humid areas with benefits including:
  - Yield increases.
  - Water and energy savings.
  - Water quality protection.

- Development and application in semi-arid regions is likely to produce similar benefits, but management strategies must incorporate the additional requirement to provide adequate leaching of salts from the soil rootzone.

- A potential and constraints survey was carried out in the intensive agricultural land of the Nile Delta, Egypt, to assess potential benefits and likely constraints to adoption of controlled drainage in such areas. The main conclusions were:

  Water saving is essential in the next 20 years. Pressures from the fixed Nile water allocation, population growth, industry and other sectors and the horizontal expansion programme mean that this need is urgent.

  However the concept of controlling drainage under crops other than rice is new. Farmers appeared sceptical (not uncommon for new ideas) but if the technique maintained (or improved) crop yields and reduced pumping and/or labour costs (as predicted), they would be interested.

- Promising water saving controlled drainage strategies were defined as those that used less water compared to conventional irrigation and drainage practice, yet maintained crop yields, soil and water resources, and reduced farmer costs. Four sustainable controlled drainage designs were developed, that allowed 8 and 14% water saving on an annual basis.

- This demonstration has shown that controlled drainage has the potential to save water, and increase crop yields in periods of water shortage, in semi-arid agricultural areas such as the Nile Delta.

- Fieldwork is underway in the western Nile Delta to test out controlled drainage and compare it to conventional practice.

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This project is being carried out by the Water Management Department of HR Wallingford in collaboration with the Drainage Research Institute of the National Water Research Centre, Egypt.

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The water management model DRAINMOD-S was supplied by kind permission of North Carolina State University. Thanks are due to Dr Glenn Fernandez and Dr Hesham Kandil for their assistance in setting up and running the model.

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IRRIGATION MANAGEMENT OF COTTON IN THE PRESENCE OF A CONTROLLED DRAINAGE SYSTEM

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ABSTRACT

A three year project evaluating management of shallow saline ground water was conducted on four 30 acre plots located in the Tulare Lake Basin of California. Cotton was grown in a clay soil using flood irrigation, sprinkler irrigation, and a combination of sprinkler followed by flood irrigation. The water table was controlled to a depth of 4 feet below the soil surface at the outlet of the subsurface drain which was installed at a depth of approximately 5 feet below the soil surface. Irrigation scheduling used leaf water potential with the depth of application based on soil water content measured with a capacitance type soil water sensor. Yields were not negatively impacted in the managed area compared to the farmer's field. The ratio of yield to applied water was greater in the research plots in the controlled drainage area than in the farmer managed plots in the controlled area. Total water application was reduced in the test plots. Maximum potential ground water contribution to crop water use occurred in the flood irrigated research plots.

INTRODUCTION

Drainage is considered a necessity for maintaining productivity in irrigated agriculture. A functioning drainage system provides salinity control, aeration, improved trafficability, and improves timeliness of agricultural operations. However, it also creates environmental problems associated with the transport of salt, nitrate, and potentially toxic trace elements, i.e., selenium and boron, into surface water. Drainage systems in irrigated areas are designed for rapid removal of drainage water and for maintaining the water depth at least 4 feet below the soil surface. This last requirement often results in over drainage, a condition in which more water is removed than is needed to maintain an aerated root zone (Doering et al, 1982) . When this occurs the potential for crop water use from shallow ground

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water is limited. Alternatives proposed for correcting this condition include using a shallow drainage design concept (Doering et al., 1982) for new construction and controlling the water table depth in existing subsurface drainage systems (Doty et al., 1975; Doty, 1980). These options have been proposed for systems in semi-humid, semi-arid, and humid areas which are not affected by salinity.

In the San Joaquin Valley (SJV) of California, drain discharge has been prohibited on 40,000 acres of irrigated land with installed subsurface drainage systems and severely constrained on an additional 90,000 acres. The San Joaquin Valley Drainage Report identified source control, land retirement, and drainage water reuse as principal methods of reducing or eliminating drain water discharge from the affected areas. Water table control to increase crop use of shallow ground water has not been extensively evaluated in arid areas and was not recommended.

Other studies demonstrated that crop use of ground water is not affected until the ground water salinity is greater than twice the Maas-Hoffman (Maas and Hoffman, 1977) salinity threshold for yield reduction in the crop (Hutmacher and Ayars, 1991). Salt tolerant crops such as cotton and sugar beet are grown extensively in the drainage impacted area of the San Joaquin Valley. Ayars and Hutmacher (1994) demonstrated that cotton will obtain nearly 50% of its water requirement from shallow ground water provided irrigation was with good quality water initially until the root system develops enough to take advantage of the ground water and then the irrigation interval is extended. This technique is most effective if the water table is maintained at a depth of approximately 4 feet below the soil surface. As the depth to water is increased the total ground water contribution is decreased (Ayars and Hutmacher, 1994). The management goal is to control the drainage discharge and maintain the water table depth.

In arid irrigated areas, the primary source of water in the shallow ground water is deep percolation from irrigation (generally surface methods) and lateral flow from other areas, either irrigated or larger watershed contributions. Research in the SJV has shown that most of the deep percolation occurs during pre-plant irrigation and the first irrigation after planting (Ayars and Schoneman, 1984). Unless this water is controlled, it will not be available later in the growing season when the crop can make use of it.

A project was developed to control the water table in an irrigated area with a saline (15 mmhos/cm) ground water to determine the potential for crop water use and the impact on soil salinity. Cotton was the crop. This paper will report on 3 years of operation of a controlled drainage system in the Tulare Lake basin in the southern part of the SJV.

MATERIALS AND METHODS

The research site was on Westlake Farms section 2, T22S, R19E located in Kings County, California. The soil in the field is classified as a Tulare clay [Fine montmorillonitic (calcareous) thermic Vertic Haplauoll]. The soil cracks to a width of 2 to 5 inches when drying and to depths of 25 to 50 inches. The average clay content ranges from 40 to 60 % and has a permeability less than 0.008 in/day. The available water is given as 0.11 - 0.12 in/in and the average pH is between 7.9 and 8.4.

The field size is approximately 570 acres and is subdivided into bays of approximately 30 acres for purposes of irrigation. A bay is approximately 270 feet wide and 5000 feet long and is irrigated using a tractor mounted pump system which delivered water at 35 to 50 cubic feet per second. Cotton was planted on the flat. The field is drained using subsurface drains installed at a depth of 5 feet with a lateral spacing of 100 feet. Approximately 200 acres is drained by the system on the south end of the field and the remainder of the field is drained by a system that drains to a sump on the north end of the field. The laterals on the south end come to a common collector main which discharged at a sump located on the east edge of the field at the south end. A control structure was placed in the sump to control the water table at a single discharge point (Schoneman and Ayars, 1999).

The field surface has a slope of 0.0004 feet/feet, resulting in a drop of approximately 2 feet in elevation over the length of the field from west to east. The water table was controlled at a depth of 4 feet on the east end of the field in 1997 and 1998. This resulted in a depth to water table of approximately 4 feet on the east end of the field and 5.5 feet on the west end of the field. The drainage system was free flowing in 1996.

There were two irrigation treatments in the first year of the experiment and three irrigation treatments in the next two years. In the first year, one bay was flood irrigated for the entire season, and the second was flood irrigated during pre-plant and with sprinklers after planting. In the following years an additional treatment was added in which the first irrigation after planting was by sprinkler and all subsequent irrigations were by flood. This was designated the combined treatment. In the first year the sprinkler irrigation was done using two laterals each a half mile long from a main located in the center of the field. In the next two years the lateral lengths were reduced to quarter of a mile with a total of 4 laterals being used off two sub-mains. The application rate both years was approximately 0.25 inches per hour. Irrigation was initiated when the leaf water potential reached approximately -14 to -18 bars. Irrigation with the flood system took approximately 5 hours compared to the one week required with multiple sets using the sprinkler system.

Depth to ground water was measured using observation wells made of 2 inch PVC pipe installed to depth of 7 feet at 3 locations in each plot. Depth to water was measured weekly and water quality samples were taken at the same time. Flow advance data were taken on the flood plots each year as were pressure distributions on the sprinkler systems. Soil water content was measured to a depth of 3.6 feet at three locations in each plot using capacitance type (frequency domain response) equipment.

Cotton (Gossypium hirsutum L) was grown in each of the three years with variety MAXXA in the first and second year and variety SJ-2 in the third year. Plant measurements included plant density, plant height, boll numbers, yield, and total number of nodes. Plant density was measured over three 20 foot long sections. Sampling at the end of the growing season determined biomass in each of the treatments. Yield measurements were determined by machine harvest. The harvested area needed to fill a module was determined and the module weight and gin turnout were used to determine lint yield.

Soil salinity was measured twice annually by soil sampling at locations near the observation wells. Sampling was done in the spring just after planting and in the fall after harvest. The soil samples were taken in 6 inch increments to a depth of 6 feet or until the water table was reached. Samples were analyzed with a 1 to 1 extract for electrical conductivity (EC), boron (B), and chloride (Cl) by the U.S. Salinity Laboratory. Bulk soil salinity distribution was determined using an EM-38[1] electromagnetic induction meter. Several transects were taken across each field .

RESULTS

Water table response, yield, soil salinity, and drainage flows are summarized in this paper. Figures 1a and 1b show the water table depth over three years of measurement. Because the drainage flow was not restricted in 1996 (Fig. 1a), the groundwater level was lower than in the two following years. In 1996 the water table position was always lower than the field drain which is not the case in the following years. The water table was highest after the first irrigation and became progressively lower over the season. The highest water table occurred under the flood irrigated plot during the entire season in 1997. The combined and sprinkler treatments were similar. Previous research has shown that the largest deep percolation occurred during pre-plant irrigation and the first seasonal irrigation. The water applied with the sprinkler systems matched the depleted soil water

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[1] Mention of trade names is provided for the benefit of the reader and does not imply endorsement by USDA-ARS.

better than was possible with the surface irrigation system. The decline in water table resulted from less applied water in 1997 and 1998 and poor control of the water table height at the drainage system outlet in 1998.

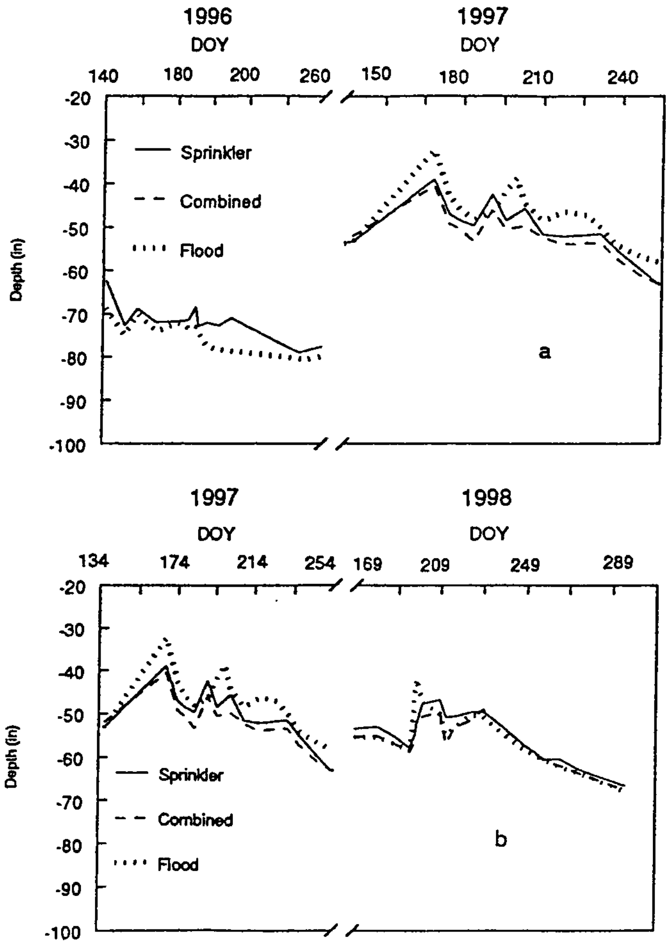

Fig. 1. Water Table Response to Irrigation Treatments at Westlake Farms as a Function of day of year (DOY) in 1996, 1997, 1998.

Figure 2 shows the drainage outflow for each cropping season. In 1996, drainage outflow was much larger than in 1997 and 1998. In 1996 the drainage outflow was not restricted and there were more irrigations applied than in either 1997 or 1998. In 1997 and 1998 one irrigation was eliminated at the end of each season. the cotton growth simulation model CALGOS indicated that this irrigation was not needed to bring the crop to maturity. Eliminating the last irrigation during the season created a larger soil water storage capacity for winter rain and pre-plant irrigation, thus reducing the drainage flow created by these water applications.

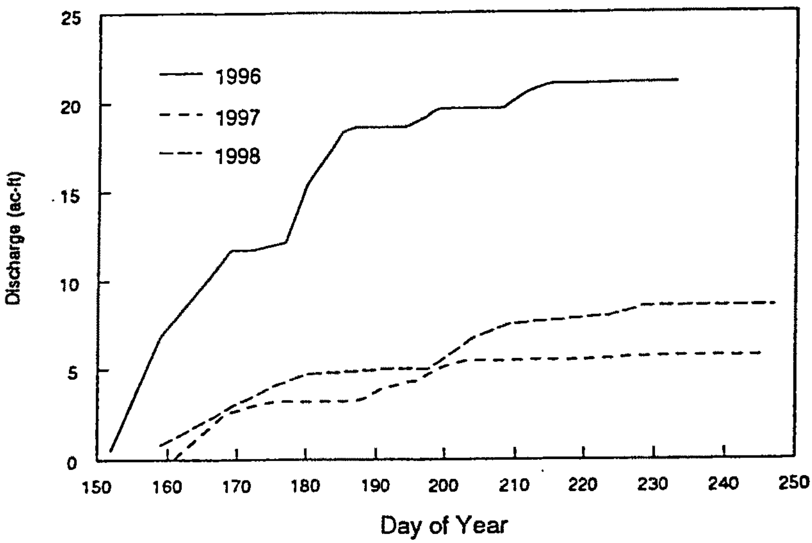

Fig. 2. Cumulative drainage From Research Plots at Westlake Farms in 1996, 1997, and 1998.

Figure 3 shows that the largest flows from approximately 200 acres of irrigated land occurred during fallow periods, both as a result of pre-irrigation and very wet winters in 1997 and 1998. Implementation of ground water control during the fallow period will help to reduce total drainage discharge. The EC of the ground water in this field is approximately 15 dS/m and is suitable for only the most salt tolerant of crops such as cotton and sugar beet.

Figure 4 shows the soil water content on the east side of the flood treatment. In the first year, soil moisture depletion between irrigations was less than in the two years. This did not have a direct effect on the cotton yield. Seed cotton yield from the flooded field was 2160, 3120 and 1997 lbs/ac for 1996, 1997 and 1998 respectively. The yield in 1998 was not really comparable with the yields in 1996 and 1997, due to a shorter growing season.

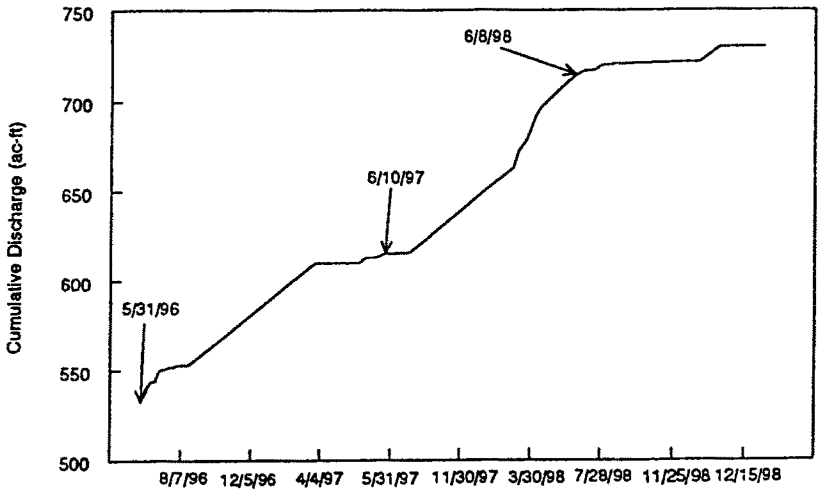

Fig. 3. Cumulative Discharge From Drains Under Research Plots and Adjacent Field at Westlake Farms.

Extending the irrigation interval was a result of using the leaf water potential instead of the calendar as the method to initiate irrigation. This resulted in more use of stored soil water and greater use of shallow ground water. More of the applied water was stored in the soil profile as a result of the increased soil water depletion, deep percolation losses were reduced, and so was drainage.

The yields are summarized in table 1. In 1996 and 1997 the flood plots had yields comparable to the yields on plots managed by the farm (farm flood). The combined plot in 1997 had the highest yield of all the plots. In 1998, the farm managed field had the highest yield followed by flood and combined plots with the sprinkler plot have the lowest yield of all. The reduced yield in the sprinkler plot was a result of water stress which occurred because the irrigation wasn't begun soon enough. Also, the yields were down in 1998 because of a late planting (an extremely wet winter). This resulted in a shorter growing season and reduced yields in general. Water applications are summarized in table 2.

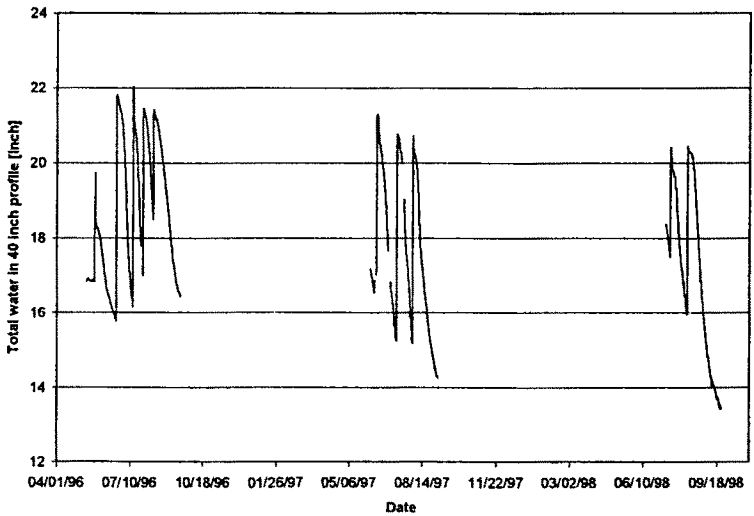

Fig. 4. Change in Soil Water Content in 3.1 Foot Profile in the Flood Irrigated Plots During Irrigation Seasons in 1996, 1997, and 1998 at Westlake Farms.

Table 1. Seed Cotton Yields (lbs/ac) on Research Plots at Westlake Farms in 1996, 1997, and 1998.

Treatment	1996	1997	1998
Sprinkler	2550	3260	1496
Combined		3310	1845
Flood	2160	3120	1977
Farm Flood	2160	3094	2040

In 1996, the sprinkler field received approximately 4 inches less water and had the highest yield of each of the plots. In 1997, the sprinkler applied the most water followed by the combined, the farm flood, and the flood plots. The sprinkler and combined plots each received one more irrigation than the flood field and the farm flood field. At the end of the season the leaf water potential values in the sprinkler and combined field indicated that one more irrigation was needed to mature the crop. This was not the case with the flood field. The farm managers

Table 2. Total Seasonal Applied Water (in) on Research Plots at Westlake Farms in 1996, 1997, and 1998.

Treatment	1996	1997	1998
Sprinkler	21.6	23.2	6.3
Combined		21.6	7.1
Flood	25.0	13.9	8.7
Flood Farm	25.0	18.1	12.6

elected to apply an additional irrigation on their fields which induced vigorous growth but no additional harvested cotton. In 1998, the total yields corresponded to the total applied water, i.e. with more water there was increased yield. There was a large increase in yield from the sprinkler to the combined and flood, but the same increase was not observed from the flood to the farm flood. What is most interesting in 1998 is the fact that relatively good cotton yields were obtained with such little applied water in all the treatments. Another way of evaluating the system is to look at the ratio of yield to acre inch of applied water. These data are summarized in table 3.

In 1996 the ratio was increased as a result of the improved irrigation schedule which included both timing and depth of application. In 1997, the ratio for the flood plots in the controlled area was the highest as a result of skipping the last irrigation. It should be noted that the farm flood field was adjacent to the test flood field and was in an area with controlled water table. Even though the yield was highest in the combined plot, the ratio wasn't the highest because of the additional applied water. The 1998 data show high ratio values because of the small applications of water. In the test plots with the controlled water table, the ratio was improved over the farm management in all three years. With some modifications of the irrigation schedule and use of controlled drainage, the farm can improve the overall efficiency of the existing irrigation system.

Table 3. Ratio of Seed Cotton Yield to Applied Water (lbs/ac/in) of Cotton Grown on Research Plots at Westlake Farms in 1996, 1997, and 1998.

Treatment	1996	1997	1998
Sprinkler	118	140	237
Combined		153	259
Flood	86	224	227
Farm Flood	86	171	162

The water balance data are given in table 4. The Et_{cp} is the potential crop water use assuming no stress during the growing season. This is not the case for the sprinkler plots in some of the years of the study. The column Et_{cm} gives the crop water use measured using the applied water, the change in water content, the runoff, and estimated drainage. The last column gives the potential ground water (PGW) contribution to crop water use and is the difference between Et_{cp} and Et_{cm}.

The maximum PGW occurred in 1998 which was a shorter growing season and had less applied water across all treatments. The flood irrigation treatments of both the research flood and the farm flood, had the largest potential contribution of shallow ground water in 1997 and 1998. There was a larger potential in the research plots than the farm managed plots due to the elimination of the last irrigation of the season on the research plots. Both of the plots were in an area with controlled drainage.

CONCLUSIONS

The results from a three year project on 4 thirty acre plots located in the Tulare Lake basin of California demonstrated the effectiveness of shallow ground water management in heavy clay soils with saline ground water. The seed cotton yield data demonstrated no loss of yield in the flood irrigated and combined sprinkler and flood irrigated plot compared to the farmer flood irrigated fields. In one of three years the sprinkler irrigated plot had a lower yield than the comparison plot, a result of excess water stress in the sprinkler plots. The ratio of yield to applied water of the research plots was comparable to or greater than that of the comparison farmer field. The controlled drainage improved the potential for ground water use from shallow ground water by maintaining a higher water table for a longer period of time and providing for one less irrigation. The maximum potential water use in all plots occurred in 1998 when the cropping season was drastically shortened due to weather conditions.

Managing shallow ground water in arid conditions with saline ground water is feasible and provides one more management tool to reduce the volume of saline drainage water requiring disposal.

Table 4. Water Balance Summary for Controlled Drainage Plots on Westlake Farms for 1996, 1997, and 1998.

Year	Et_{cp} (in)	Applied Water (in)	Drainage + Runoff (in)	Δ SW (in)	Et_{cm} (in)	PGW (in)
Sprinkler						
1996	27.6	22.0	2.0	8.0	28.0	0
1997	30.6	23.3	0.7	8.0	30.6	0
1998	29.0	6.2	0.0	8.0	14.2	14.8
Combined						
1996	27.6	0	0	8.0	0.0	0
1997	30.6	21.6	0.7	8.0	28.9	1.7
1998	29.0	7.1	0.2	8.0	14.9	14.1
Flood						
1996	27.6	25.0	6.0	8.0	27.0	0.6
1997	30.6	14.0	0.6	8.0	21.4	9.2
1998	29.0	8.7	0.6	8.0	16.1	12.9
Farm Flood						
1996	27.6	25.0	6.0	8.0	27.0	0.6
1997	30.6	18.2	0.6	8.0	25.6	5.0
1998	29.0	13.0	0.6	8.0	20.4	8.6

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PREINOCULATION WITH VA MYCORRHIZAL FUNGI INCREASES PLANT TOLERANCE TO SOIL SALINITY

Isabella C. Cantrell[1] Robert G. Linderman[2]

ABSTRACT

The loss of land for the production of agricultural crops due to salinity is a major problem worldwide. The means to deal with saline soils by the development of salt-tolerant crops, by leaching, or by using desalinized water are not feasible for many developing areas of the world. VA mycorrhizae (VAM) are known to alleviate salt stress on plants, but a practical method to establish them has not been developed. Preinoculation of lettuce or onion plants with mixtures of VAM fungi cultured from saline or nonsaline soils before transplant into sodic soils was shown to be an effective means of increasing plant tolerance to salt toxicity. This method could be practical for farmers needing to grow crops on saline soils.

INTRODUCTION

In light of the expanding human population of the world and the finite amount of agricultural land useful for food production, there is great need to increase production capacity for the future. Irrigation will play a major role in increasing the land base for agricultural production, but many irrigation systems have failed to increase productivity, and in fact have contributed greatly to the increase in salinity of soils, for various reasons, with the ultimate result of decreasing crop production potential due to salt toxicity. Reducing salinity effects by developing improved salt-tolerant crops, by leaching excess salts with fresh water, or desalinizing seawater for irrigation purposes have been successful in many areas of the world. However, most of those methods are beyond the economic means of the developing parts of the world.

Vesicular-arbuscular mycorrhiza (VAM) is a mutualistic symbiotic association between specialized soil fungi and the roots of most of the plant taxa grown in agriculture. The VAM association is known to reduce the impact of soil salinity on plant growth and productivity. Reports indicate that the effect is primarily one of improving phosphorus (P) nutrition of the host plant, thereby making it more tolerant of salinity. All reports, however, have added salts to the soil after plants were colonized by VAM fungi. Progressive addition of salts does not simulate real farm conditions.

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There are no reports on the preinoculation of transplants with VAM fungi prior to planting in saline soil. We hypothesized that preinoculation would increase salt tolerance and would be a practical approach that farmers could adopt. We also hypothesized that VAM fungi from a saline soil would be more effective than those from a nonsaline soil in reducing deleterious effects of salinity on plant growth. We tested these hypotheses on lettuce and onions in soils amended with sodium chloride (NaCl).

Materials and methods

VAM fungal inoculum mixtures were developed in trap cultures from two sites in Oregon: Burns (saline) or Corvallis (nonsaline) and used at approximately equivalent inoculum levels to inoculate lettuce or onion seedlings in 25 cc plug cells. Seedlings were grown for 18 (lettuce) or 29 (onion) days before transplanting into saline soil treatments. The Newberg series base soil was amended with NaCl solutions to achieve increasing sodic levels: EC 2 (control), EC 4, EC 8, and EC 12 dS/m as measured by electrical conductivity. The experiments were conducted under greenhouse conditions for 10 weeks. Plants were fertilized weekly with nutrient solution without P from week 3-10. All transplants received sufficient nitrogen to avoid deficiency, and were watered daily by weight to avoid leaching. The base soil had 27 ppm available P and had a high P-fixing capacity as determined by limited growth of onion plants treated with high (22.5 mg kg^{-1}soil) levels of inorganic P.

Measurements on color (chlorophyll) of lettuce leaves were made during the experiment. At harvest, root and shoot mass was determined for both plant species, and the extent of root and soil colonization by VAM fungi was measured. Also, mineral content of plant tissue was analyzed, and the residual salt content (conductivity) in treatment soils was determined. An additional experiment was conducted to determine the effectiveness of added inorganic P fertilizer to alleviate salt damage as compared to the effectiveness of VAM.

Results

Inoculation with either source of VAM fungi (saline or nonsaline) effectively reduced effects of soil sodicity on plant growth of both lettuce and onion. At the highest salt level (EC 12 dS/m), dry mass of nonVAM lettuce shoots was 29% less than for VAM plants; dry mass of lettuce roots was 23% less for nonVAM plants than VAM plants. Dry mass of nonVAM onion shoots was 88% less than for VAM plants; dry mass of nonVAM onion roots was 73% less than for VAM plants (Figure 1). Decrease of chlorophyll content of lettuce leaves at the highest salt level was significantly lessened by VAM. The increased tolerance to salt damage by VAM was greater with onion than lettuce, because onion was more highly responsive to VAM than was lettuce under the P-limiting conditions of the experiment. Adding more P to nonVAM onions only partially alleviated the salt

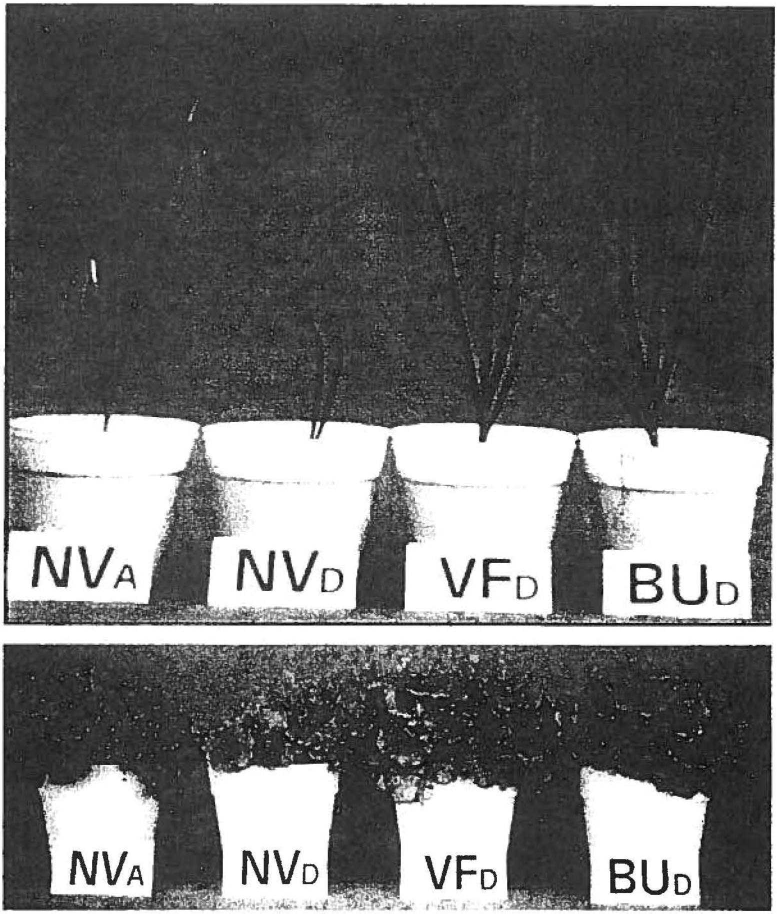

Figure 1 shows onions (above) and lettuce plants (below) grown in soil treated with different levels of NaCl solutions (A= control/ no salt, D= highest level at 12 dS/m). Fungal treatments were: NV= nonVAM, VF= Veg Farm VAM fungi, or BU= Burns VAM fungi. At 12 dS/m, shoot dry weight of NVplants was less (29% for lettuce; 88% for onions) than that of the VAM plants combined from the Veg Farm and Burns inocula.

effects due largely to the high P-fixing capacity of the soil. VAM plants absorbed more nutrient elements (e.g. P, Cu, Zn), including Na, than nonVAM plants, but by some mechanism reduced the impact of higher Na content on plant growth functions. VAM colonization of roots was reduced as salt level increased, more with the nonsaline soil source (Corvallis) than the saline source (Burns). Final EC of noninoculated soil was significantly higher than that of soil inoculated with VAM fungi due to reduced plant uptake.

Conclusions

The hypothesis that preinoculation of transplants with VAM fungi would be an effective means of increasing plant tolerance to soil salinity was verified. The hypothesis that VAM fungi from a saline site would be more effective than those from a nonsaline site was not verified, although there were some differences between the fungal sources in their effects on plant responses (e.g. absorption of some elements). The method of preinoculation with VAM fungi would be an effective and useful tool for farmers to use to overcome effects of soil salinity on plant growth, and it appears to be more effective than adding more P fertilizer, especially in soils with high P-fixing capacity as the one used in our experiment.

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APPLICATION OF PLANT NUTRIENTS THROUGH IRRIGATION WATER

JOHN G. CLAPP [1]

ABSTRACT

The application of plant nutrients through irrigation water is one of the most efficient methods for fertilizer application to enhance crop production and reduce or eliminate potential environmental problems related to direct soil surface fertilizer applications. Stable clear liquid fertilizers are usually preferred for fertilization as compared to solid materials which must be solubilized before use, especially for drip irrigation systems. Tessenderlo Kerley produces a number of clear liquid products which have proven to be useful for fertigation. One of these products KTS (potassium thiosulfate) has been evaluated by several researchers for use in sprinkler and drip irrigation systems.

INTRODUCTION

The practice of applying plant nutrients through irrigation systems, known as fertigation has been used since the 1930's. Anhydrous ammonia was applied through irrigation water in California before liquid fertilizers became available (Ransdell, 1968). Fertigation began to expand rapidly in the 1950's when nonpressurized sources of liquid nitrogen became available.

Today, the application of plant nutrients through irrigation water is one of the most efficient methods for fertilizer applications to enhance crop production and reduce or eliminate potential environment problems such as runoff from broadcast surface applied fertilizers, ground water nitrate contamination from single nitrogen applications, etc.

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FERTILIZER APPLICATIONS

In order to avoid clogging of irrigation systems, fertilizers must be very soluble and compatible with the irrigation water. Stable liquid fertilizers have proven to be well suited for application through all types of irrigation systems. Solid fertilizers are widely used, but must be solubilized without leaving a residue of clay or wax. Fertilizers vary greatly in their solubility (Burt et al, 1995). These solubilities are illustrated in Table 1.

Clear liquid fertilizers are well suited for application through irrigation systems, especially low volume systems. These products can be metered into irrigation systems with a minimum of equipment and save time since the nutrients are already in a soluble form and ready to use. Some products currently being used in low volume systems include urea-ammonium nitrate solutions, phosphoric acid and potassium thiosulfate.

SPECIALTY LIQUID FERTILIZER PRODUCTS

Tessenderlo Kerley currently is the largest manufacturer of specialty liquid fertilizers in the world. Since the development of ammonium polysulfide - ammonium hydroxide and ammonium thiosulfate in the 1950's the specialty product line has continued to expand through new product development and acquations (Clapp, 1998). In addition to being the largest manufacturer of ammonium thiosulfate (THIO-SUL) in the world, Tessenderlo Kerley also developed and is the largest manufacturer of potassium thiosulfate (KTS).

The company purchased the control release triazone nitrogen technology (Clapp and Purham, 1991) from the Accadian Corporation in 1993. This form of nitrogen (urea-triazone) is used in the formulation of several clear liquid products used for foliar and fertigation applications. Some of these products are summarized including their characteristics in Table 2.

These products have been evaluated in several field trials for application via irrigation waters. Zink (1998) reported a significant increase in potato yields when potassium thiosulfate (KTS) was added through a center pivot irrigation system in the San Luis Valley of Colorado. His evaluation included the addition of KTS to the recommended rate of soil applied potassium as potassium chloride over a three year period. These results are summarized in Table 3 and show that the addition of KTS applied through the overhead irrigation water increased potato yields by an average of 12% over the three year period.

A similar study was initiated in 1997 on cotton in Missouri (G. Stevens, unpublished data) with KTS being applied through overhead irrigation water. Results from this preliminary study are summarized in Table 4. Cotton yields were increased when all or part of the potassium was applied through sprinkler irrigation as compared to a soil application.

Three potassium sources were evaluated through drip irrigation for apple production in New York (W.C. Stiles, unpublished data, 1995). Results are summarized in Table 5.

A drip fertigation trial was conducted in North Carolina (D.C. Sanders, unpublished data, 1997) to evaluate nitrogen and potassium sources for tomato production. These treatments and results are summarized in Table 6. The clear liquid products, TRISERT - CB and KTS worked very well in this system and gave a higher yield than other products which first had to be solubilized.

SUMMARY

The application of plant nutrients through irrigation water is a standard method to enhance crop production in many commercial operations. The use of clear liquid fertilizer sources eliminate the problem of dissolving solid material prior to injection into irrigation water. For drip irrigation systems, solid materials may result in plugged emitters unless completely dissolved.

New clear liquid products such as KTS (potassium thiosulfate) have proven to be an effective and easy to use source of plant nutrients for fertigation.

Table 1. SOLUBILITY OF FERTILIZER MATERIALS

	Grade	Solubility gm/100ml
<u>Nitrogen Fertilizers</u>		
Ammonium Nitrate	34-0-0	18.3
Ammonium Polysulfide	20-0-0	high
Ammonium Sulfate	21-0-0	70.6
Ammonium Thiosulfate	12-0-0	v. high
Anhydrous Ammonia	82-0-0	38.0
Aqua Ammonia	20-0-0	high
Calcium Nitrate	15.5-0-0	121.2
Urea	46-0-0	100.0
Urea Sulfuric Acid	28-0-0	high
Urea Ammonium Nitrate	32-0-0	high
<u>Phosphate Fertilizers</u>		
Ammonium Phosphate	8-24-0	moderate
Ammonium Polyphosphate	10-34-0	high
Ammonium Polyphosphate	11-37-0	high
Phosphoric Acid, green	0-52-0	45.7
Phosphoric Acid, white	0-24-0	45.7
<u>Potash Fertilizer</u>		
Potassium Chloride	0-0-60	34.7
Potassium Nitrate	13-0-44	13.3
Potassium Sulfate	0-0-50	12
Potassium Thiosulfate	0-0-25-17S	v. high
Monobasic Potassium	0-52-34	33

Micronutrients			
Borax	11%	B	2.10
Boric Acid	17.5%	B	6.35
Solubor	20%	B	22
Copper Sulfate (acidified)	25%	Cu	31.6
Cupric Chloride (acidified)			71
Gypsum	23%	Ca	0.241
Iron Sulfate (acidified)	20%	Fe	15.65
Magnesium Sulfate	9.67%		71
Manganese Sulfate (acidified)	27%	Mn	105.3
Ammonium Molybdate	54%	Mo	43
Zinc Sulfate	36%	Zn	96.5
Zinc Chelate	5%-14%	Zn	v. sol.
Manganese Chelate	5%-12%	Mn	v. sol.
Iron Chelate	4%-14	Fe	v. sol.
Copper Chelate	5%-14%	Cu	v. sol.
Zinc Lignosulfonate	6%	Zn	v. sol.
Manganese Lignosulfonate	5%-14%	Cu	v. sol.
Iron Lignosulfonate	6%	Fe	v. sol.
Copper Lignosulfonate	6%	Cu	v. sol.
Lime Sulfur			high
Sulfuric Acid	95%		v. high

Table 2. TYPICAL PROPERTIES OF TESSENDERLO KERLEY'S LIQUID FERTILIZER PRODUCTS

Product Trade Name	Grade	% of Total N as SRN	Spec. Grav. @15°C	gms. Total N Per Liter @15°C	gms. Other Plant Nutrient Per Liter @15°C	Salting Out Temp °C	Typical pH
KTS®	0-0-25-17S	0	1.460	0	360K2O, 252S	- 9	7.0-8.2
FORMOLENE-PLUS®	30-0-0	60	1.285	385	0	- 18	9.5
N-SURE®	28-0-0	72	1.287	360	0	- 18	9.5
N-SURE® -LITE	30-0-0	50	1.261	378	0	- 18	9.5
THIO-SUL®	12-0-0-26S	0	1.327	160	344S	- 7	7.2-8.0
TRISERT®	13-3-4	50	1.179	156	36 P2O5, 48 K2O	- 7	9.5
TRISERT® -CB	26-0-0.5B	33	1.223	324	6B	- 18	8.7
TRISERT® -KS	15-0-12-8S	60	1.357	204	168 K2O, 108S	- 18	10.3
TRISERT® -KSB	26-0-5-3S-0.3B	33	1.306	336	65 K2O, 40S, 4B	- 18	9.5
TRISERT® -NB	26-0-0	33		316	0	- 18	8.7
TRISERT® -VG	9-6-8-0.1 FE-0.05ZN-0.05Mn-0.05Cu-0.02B-0.0005Mo	33	1.224	110	72 P2O5, 96 K2O	- 10	9.9
TRISERT®-VGH	9-6-8	33	1.224	108	72 P2O5, 96K2O	- 10	9.7
NFE™	16-0-0-4Fe	0	1.330	214	53Fe	- 17	7.5
NMG™	14-0-0-4Mg	0	1.345	188	54Mg	- 8	6
NZN™	15-0-0-5Zn	0	1.136	198	66ZN	- 8	4

Table 3. POTATO RESPONSE TO KTS VIA IRRIGATION WATER

	Yield - T/ha			
Treatment	1995	1996	1997	Avg.
No K_2O applied	-	44.6	31.9	-
Recommended K_2O	23.7	49.4	34.9	36.0
Recommended K_2O + Fertigation with KTS	26.7	52.2	42.4	40.4
LSD .05	2.4	5.0	4.9	4.1

Table 4. COTTON RESPONSE TO K FERTIGATION

Treatment[a] -K_2O kg/ha		Yield
Soil	Sprinkler	kg/ha
0	0	1061
39	0	1056
19.5	19.5[b]	1116
0	19.5[b]	1176
0	19.5[c]	1112

a KCl used for soil application, KTS used for application via overhead irrigation.
b One application at first bloom.
c Two applications (first bloom and two weeks later).

Table 5. APPLE RESPONSE TO K SOURCES APPLIED VIA DRIP IRRIGATION

	Tissue %K				
K Source[a]	June	July	Aug.	Sept.	Oct.
KTS	1.68	1.54	1.27	1.06	.99
K_2SO_4	1.59	1.44	1.24	1.06	.92
KCl	1.54	1.46	1.26	1.01	.90

a Five monthly applications (May-Sept.) at 13 kg/ha K_2O

Table 6. TOMATO RESPONSE TO NITROGEN AND POTASSIUM SOURCES VIA DRIP IRRIGATION

Treatment [a]		Yield - T/ha		%
N-Source	K-Source	Total	Marketable	Cull
$CaNO_3$	KCl	43.5	33.8	18
$CaNO_3$	KNO_3	44.4	31.6	27
$CaNO_3$	KTS	45.7	33.4	23
T-CB[b]	KTS	47.5	38.1	12

a N and K_2O applied during growing season at 78 and 157 kg/ha, respectively.
b TRISERT - CB (26-0-0-5B)

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MANAGING A LARGE IRRIGATION SYSTEM UNDER EMERGENCY CONDITIONS: HIRAKUD PROJECT CASE STUDY, INDIA

B.P. Das[1] J.M. Reddy[2]

ABSTRACT

In Hirakud, a multi-purpose project, in India, rice is grown over an area of 160,000 ha during the monsoon season (June to October). Supplementary irrigation of 100 mm in September and 150 mm in October is needed. Often, due to erratic monsoon and lean rainfall in September/October, supplementary irrigation of 150 mm to 200 mm per month is needed. The crucial supplementation for crop maturity occurs during September 25 to October 25, after which the demand tapers off.

On October 5, 1984, a normal monsoon year, an emergency situation occurred due to the collapse of the left upstream river wingwall (of 15-m height). The command area of 85,000 ha below the aqueduct was consequently deprived of irrigation when 50 % of the command area was in dire need of 5 to 7 cm of supplemental irrigation during flowering stage of the rice crop.

After the collapse of the wingwall, an appropriate canal operation strategy was developed and implemented to ensure supply of water during the rehabilitation period to selective and needy areas on a priority basis. By innovative rehabilitation technique, the structure was put into commission by October 25, 1984, when partial water supply was resumed through the structure. By farmers' participation, appropriate production practice demonstration, and ensuring rotational water supply matching with crop water need (FAO 24, 1977), almost 75,000 ha received satisfactory irrigation. In spite of the reduced water supply, the crop yield in the project area was 20 % more than the normal yield.

INTRODUCTION

Mahanadi, the largest river in the state of Orissa has been harnessed by building a dam at Hirakud (1957), intercepting 83000 sq. km of basin area. The multipurpose objectives served by the dam are: to moderate large flood inflows of 2 M Cusec to 1 M Cusec, the safe carrying capacity of the river at the head of the delta, 300 km downstream from the dam; to generate hydropower with an installed capacity of 270 MW (later augmented to 307 MW); and to provide

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irrigation to 159,000 ha with an annual cropping intensity of 165 %. Two main canals, Bargarh Canal on the right (capacity 115 m^3/sec to serve 135,000 ha), and Sason Canal on the left (capacity 20 m^3/sec to serve 24,000 ha) provide irrigation water to the command area.

The perennial power release of a minimum of 300 m^3/sec has been harnessed by a new weir built at the head of the delta. This has brought an additional (1967) 130,000 ha under irrigation in the 100 year-old Mahanadi delta command. The overall command of 0.3 M ha in the Mahanadi delta now has a cropping intensity of 150%. By using a multiple cropping pattern, the delta has been transformed from a poverty-stricken, food-deficient region into a prosperous food-surplus region. There has been a dramatic increase in the productivity of rice crop. The yield has increased from 1 ton/ha over 0.1 M ha in 1957 to 3 to 4 tons/ha in the monsoon (June-October), and 5 to 6 tons/ha in the summer (January-April) of 1998 over an area of 0.25 M ha. The yield is comparable to Southeast Asian countries adopting modern farming practices. The average farm income has gone up from Rs 500/ha (US $80) in 1957 to Rs 12000/ha (US $300) in 1998, primarily due to the introduction of irrigation.

COMMAND AREA CHARACTERISTICS AND THE CANAL SYSTEM

In the above context, the Bargarh main canal, a contour canal of 85 km, conveying 115 m^3/sec at the head of the project functions as a lifeline to 70,000 farming families spread over a command area of 135,000 ha. The contour canal is aligned in moderately deep-cutting and filling (10 to 12 m), and is provided with a large number of cross-drainage structures over major and medium drains. The terrain slopes down (1 in 300) from the main canal to the Mahanadi and the Ong rivers which form the boundary of the command (Figure 1). The soil types in the command vary from clayey silt (25%) to medium textured (40%), and light textured (35%). There are highly pervious patches close to the main river covering 5% of the command, where light duty crops are grown.

Four large rivers with catchment areas of up to 500 square km cross the main canal through major aqueducts with ventage varying from 150 to 250 m. These rivers have pervious alluvial material on the banks at the crossing sites. The canal generally runs in heavy fillings of 15 to 20 m over a 200 to 300 m stretch at the approach and exit of each aqueduct, where earthen banks are constructed, conforming to a stable earth dam profile, retaining water with a potential head of 10 to 15 m. The earthen conveyance section is flumed (up to 60%) to a reinforced concrete trough through transitions which are supported on abutments and piers. All the aqueducts undergo periodic inspection in addition to a detailed annual inspection during the summer closure (May/June) through a Safety Assurance Program (SAP). The first aqueduct is at the 30th kilometer of the main canal over the river Danta, below which the command area is 85,000 ha.

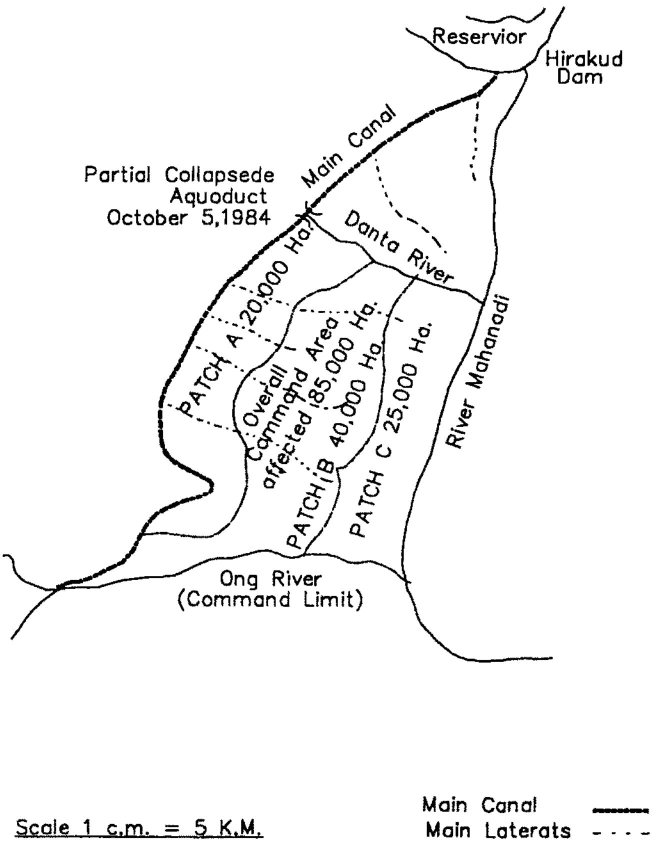

Figure 1. Index Map of Hirakud Canal System

STRUCTURAL DISTRESS/PARTIAL COLLAPSE OF THE DANTA AQUEDUCT

Structural Details

A normal trapezoidal channel with a bed width of 20 m is flumed to 12 m wide reinforced concrete boxed trough supported on end abutments and piers spanning 130 m of water way, corresponding to the bankful stage. The river spreads to 600 m during high flood that necessitates 200 m long, 15 m high earthen banks as approaches for entry and exit.

The river flows through the two 15 m high abutments of rubble masonry and each abutment is provided with two 50 m long training walls on the upstream and downstream. Each training wall slopes down from a height of 15 m at the junction of the abutment to 3 m at the toe of the canal bank at the river edge. The abutment and wing wall designed as retaining walls are supported on 12 m deep 3 m outer diameter wells with reinforced concrete steining. The wells were founded on firm incredible weathered rock/form clay. The well cap supporting the walls was only 2 to 3 m below the river bed which was erodable up to 8 m being of silt, fine sand to coarse sand. A 10-m wide and 1 m thick launching flexible rubble apron was provided against the wall to protect the foundation against scour.

Transition to the reinforced concrete trough was through canal wings of 20 m length on shallow foundation in firm ground that was rising slowly from the river edge. Essentially, the canal wings, river wings with well compacted earthen banks, which were lined with concrete on the canal section formed a seepage barrier against 15 m of hydraulic head (canal full supply level to river bed level). A creep length of 60 m was provided with the assumption that the river bed at the toe of abutment/wing wall will not erode dangerously (by provision of launching apron) to facilitate a piping path to develop. The river and canal wings were provided with 0.5 m thick filter backing with deep holes on the river wings for keeping the backfill unsaturated. A base width of only 0.3 to 0.4 height of the wall was considered adequate and was provided with the above assumption. Figure 2 details the aqueduct structure.

SEQUENCE OF EVENTS LEADING TO DISTRESS ON OCTOBER 5, 1998

Following 150 mm of rainfall between October 1, 1984 and October 5, 1984, a medium flood of 5 m depth occurred at the aqueduct, which led to 1 m subsidence of the apron over a 5-m diameter patch, protecting the left upstream wingwall. Some boiling was noticed. The distress that occurred from the evening of October 5, 1984, is detailed below:

- muddy water exited on the river bed at the boil area around 6 P.M., which within half an hour became a turbulent boil (about 10 m upstream from the junction of the wing wall and abutment)

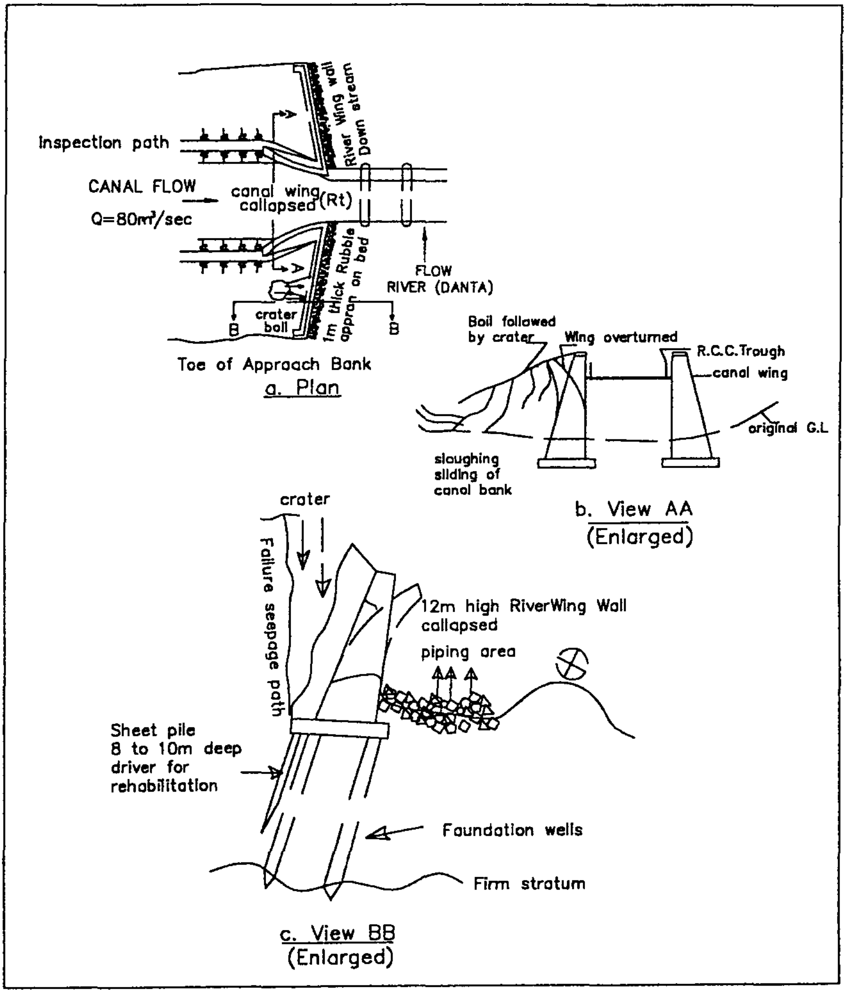

Figure 2. Partial Collapse of Danta Aquaduct

- sudden collapse of the earth slope between the right upstream canal wing and left upstream wing occurred over a 5 m diameter patch leading to a crater, through which water from the canal was flowing

- a 10 m stretch of canal wingwall collapsed against the crater and 50 m^3/sec out of the canal discharge of 80 m^3/sec flowed out under and over the collapsed canal wing and exited under the river wing causing the protective rubble apron to move out over almost a 10 m stretch, with violent noise; the residual head at the boil location was almost 5 m.

- a large mass of saturated earth flowed from the crater adjacent to the canal wing and literally pushed a 20 m stretch of 10 m high river wing wall to overturn into the river, about 2 m above the well cap; all of this resulted in a substantial collapse of the right protective transition upstream of the trough, which remained firmly seated on the abutment. Figure 2 details the damages that occurred.

- the supply at the head of the main canal was closed by 7 P.M., following evidence of piping on the river bed, but the volume of water in the 30 km reach of main canal of 3 m depth continued to flow into the river, substantially aggravating the damage until 7 A.M. on October 6.

With 85,000 ha of command area below the aqueduct where crop needed supplementation of 5 cm to 10 cm for maturity, two crucial issues had to be addressed following this sudden disaster:

- managing water distribution below the aqueduct.
- rehabilitating the collapsed right upstream appurtenances at the earliest opportunity to resume supply.

A senior management group was assembled in the early morning of October 6, 1984, to work out a strategy to be implemented on war footing so that the aqueduct would become operational within 15 days to carry at least half of the original design supply.

WATER MANAGEMENT DOWNSTREAM FOLLOWING FAILURE

A management strategy was formulated with the objectives of:

- Increasing the chances of survival of the crop over as much of the command area of 85,000 ha as possible.
- assessing the crop water need realistically and ensuring supply for obtaining good yield at least over 80% of the command area.

Crop Survival

By noon on October 6, all regulating shutters on the main canal and laterals were fully closed to conserve and store water by forming a reservoir covering 1400 km of major and minor channels of varying width of 1 m to 20 m and depth of 0.5 m to 3 m. The stored water was assessed as 200 ha-m.

The cropped area needing irrigation, 80,000 ha as non-paddy, and early paddy over 5,000 ha, was maturing by October 10. The cropped area could be realistically delineated into three distinct patches as shown in Figure 1. Patch A: covering the head 30 % of the command, Patch B: covering the central 45% of the command, and Patch C: covering the tail 25% of the command. The crop condition over any patch was essentially the same, because of the transplanting dates that were staggered by 10 days from patch to patch.

In Patch A, a medium duration paddy (June 25 through October 10) was grown with better water availability, to enable growing a second pulse/oil seed crop (November-January) and a third summer paddy crop from January through May. In the central Patch B, 50% of the area (20,000 ha) was covered with medium paddy maturing by October 25 and the rest with long duration variety maturing between October 31 to November 5. A second crop of summer paddy (January—May) was grown over half of the command area along with pulses, oil seeds, and vegetables. Over Patch C, only 20% was covered with medium duration paddy maturing by November 10 and the rest by November 15 to 20.

Essentially, the irrigation need over the tail patch (where 30 to 40% is low clayey soil, supporting long duration), is felt up to October 31 in good and average years (monsoon rainfall 1000 to 1200 mm), and to November 7 in bad years (monsoon rainfall 800 to 900 mm). It is the erratic nature of the rainfall, particularly when the monsoon does not become active until the middle of July (transplantation need of 150 to 200 mm is substantially wet from monsoon) and when the monsoon recedes in early September when the balance crop water need is at least 200 mm (gross). Such situations call for extremely careful, rotational management by active participation of farmers.

WATER MANAGEMENT STRATEGY

The first task was to assess the realistic consumptive use for the paddy at/prior to maturity stage in each patch. The background information that was gathered revealed the following:

- 3 to 5 cm of water was ponded over 20,000 ha of Patch A.
- 1 to 2 cm of ponded water was available over 20,000 ha of Patch B (tail half) and the upper half of 20,000 ha had 2 o 3 cm ponded water.

- Patch C of 20,000 ha was just moist at field capacity and most of the pervious patches needed immediate watering.

The flowering and milk ripe stage of maturity has the highest ET need of 3 to 5 cm and any reduction of water would cause disproportionately large reduction in crop yield. Based upon the crop stage, the soil-water depletion, consumptive use and irrigation application quantity were decided as shown in Figures 3a, b, and c.

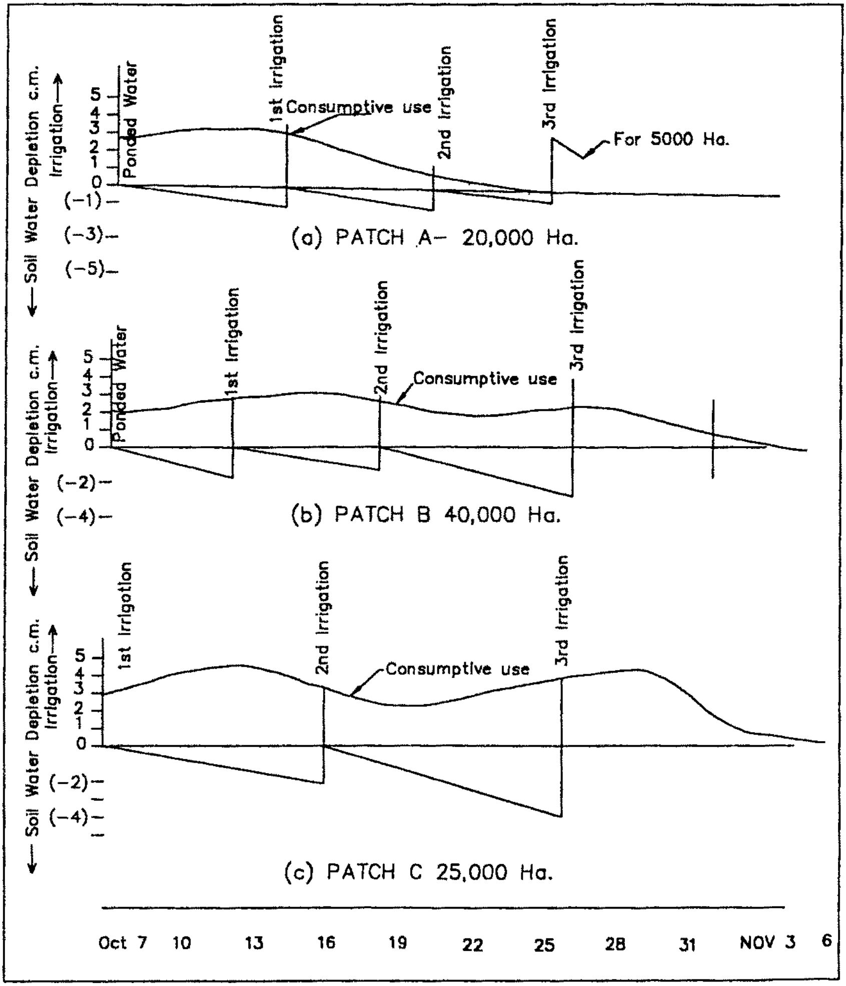

Figure 3. Schematic Description Between Soil-Water Depletion, Actual Irrigation and Crop Consumptive Use (Paddy)-October 7th through November 6

Water Management From October 7 Through 13

Because of availability of 4 cm of ponded water in Patch A, water supply was totally stopped to 20,000 ha. In Patch B, over the upper 20,000 ha with a minimum of 2 cm of ponded water, supply was shut off for 4 days (October 7 through 11). The lower 20,000 ha was provided with 2 cm between October 7 through 11).

In Patch C, the entire 20,000 ha was given 5 cm between October 7 through 13, with the objective of making the crop survive, but it became clear that over the absolute tail area of 5000 ha, the flowering just did not occur. Rainfall of 2 to 3 cm occurred over Patches B and C between October 10 through 15, helping irrigation management significantly.

Water Management From October 13 Through 20

By October 11th, almost the entire Patch A had no ponded water, but the root zone being at field capacity, 2 cm was supplemented to the upper and middle areas of 10,000 ha and only 1 cm was allowed to the lower 10,000 ha, starting from October 13.

For Patch B, in a staggered fashion, 2 cm was given to the upper 20,000 ha from October 13. For the lower 20,000 ha of Patch B and about 15,000 ha of Patch C water was allowed just to keep the surface wet, to prevent development of shrinking cracks. By October 20, the entire reservoir over the canal network dried up, but with the rainfall almost 40,000 ha in Patches A and B had minimal need (less than 1 cm as milk ripe stage was reached).

It was anticipated that by October 20, the partial rehabilitation would enable resumption of supply through the aqueduct, but another 5 days were needed for starting half supply. Even pushing 20 m^3/sec through the canal on October 21 did not succeed.

Between October 21 and 25, almost 5,000 ha out of the paddy coverage of 80,000 ha had totally withered, but the remaining 75,000 ha had healthy crop, of which the tail 30,000 ha was in immediate need of watering (flowering starting over 15,000 ha and the rest in milking stage).

Through an innovative rehabilitation strategy, the aqueduct became operational on the night of October 25 and almost 40 m^3/sec was pushed downstream on the morning of October 26. Between October 26 and November 10, a gross supplement of 150 mm was given to 40,000 ha in the tail and 50 mm to needy patches, which successfully met the crop water need of 75,000 ha of paddy crop by and large. The key favorable factors were:

- cloudy skies reduced evaporation loss
- no water was allowed to spill to the draining channels, which normally carry 10 to 15% of the overall discharge.
- farmers were constantly guided by agriculture extension service officials on application of fertilizers (before flowering) and not to pond up more than 1 centimeter or so to reduce deep percolation loss.
- the assurance that was given that this structure would be rehabilitated in 10 to 15 days did materialize.

REHABILITATION TECHNIQUE: IMMEDIATE AND LONG-TERM

Immediate Remedial Works

As the canal wingwalls and the river training walls with rubble apron at the river bed were the main barriers against uncontrolled seepage, their restoration above the firm broken surface was considered emergent. But a trial barrier just upstream of the river wing by steel sheet piles driven to clay with a capping beam was considered an essential appurtenance. The sequence of activities were:

- de-watering and drying the scoured bed over 50 m x 70 m of 10 to 12 m depth to rebuild the walls and retaining bank; excavating and banking the slushy material (5000 m^3)—October 7 through 11.

- re-building the collapsed stretches of canal wingwall (20 m long) and upstream river training wall (15 m long) with reinforced concrete wall by buttressed support; prosper keys were introduced into the old edges—October 9 through 20.

- driving 8 to 10 m deep steel sheet pile over 20 m length just upstream of the well cap to cover the broken zone of river wingwall; large pieces of rubble masonry from the broken canal wingwall moved 30 m and were blocking the pile path; the pile line was, however, taken to rest on hard clay/weathered rock to prevent any possibility of soil movement in between the foundation wells; the sheet piles were capped by a reinforced concrete beam which was tied to the well cap—October 10 through 15

- clayey soil was compacted below optimum moisture content in 0.15 m thick layers between the reconstructed canal and river wingwalls, pneumatically tamped in 0.05-m thick layers (foundation of canal and river wing junction of sheet pile)—October 10 through 23.

- a well-designed 1 m thick filter layer was laid at the back of the river wing along with weep hole to safely drain any seepage water—October 20 through 24.

- the displaced rubble apron on the river bed was thoroughly cleared and a 5 m wide, 1 m thick graded rubble apron was added to ensure safe exit gradient to seepage and also safety against scour during high floods—October 20 to 24.

All these activities were carried out continuously over three shifts a day for 18 days, supervised by 10 senior executives.

Long-Term Remedial Works

A critical analysis of the failure revealed that uncontrolled piping led to the failure, but the failure of both canal and river wings were due to inadequate section to retain the over-saturated soil mass as a gravity structure. The base width of 0.3 to 0.4 of height of surcharge was certainly inadequate. The basic assumption of dry backfill, assuming satisfactory functioning of this filter backfill provided was deficient. Further, in order to ensure a safe seepage path for the large head difference between the canal full supply level and the river bed level. It was decided to extend the reinforced concrete trough section by 70 m upstream, where the canal bank is only 5 m in height. The extension of the reinforced concrete trough supported on piles was carried by underwater technique, deploying barges on the running canal. The canal supplied irrigation, industrial and drinking water throughout the year. The short-term remedial works (October 1984) cost Rs 4 M, and the long-term (1985-1986) cost Rs 15 M, against the original structure cost of Rs 1 M (1955-1957).

WATER USE AND YIELD

Against a normal supplementation of 0.40 to 0.45 m (400-450 mm) in average and bad years, the overall supplementation in 1984 was only 0.34 m over the command area of 75,000 ha below the aqueduct.

To assess the impact of deficit irrigation supply (anxiety was shown by the farmers), detailed crop yield data was collected over 189 villages. It came as a surprise that, over 150 villages (65,000 ha), the yield on the average was 3.2 T/ha against 2.5 to 2.7 T/ha recorded between 1960 to 1983. The reason attributed by the Directorate of Agriculture, Orissa, was that better aeration of the crop root zone (due to drying of soil) resulted in full filling of the grain and reduced the chaff to a minimum.

LESSON LEARNED AND CONCLUSION

Danta Aqueduct, a major hydraulic structure, on an 80 m^3/sec canal collapsed due to scour, subsidence, and failure of masonry wingwalls protecting the high approach bank, and functioning as transition from earthen trapezoidal section to reinforced concrete trough section. Uncontrolled seepage occurred from a high hydraulic head of 15 m between the canal full supply level and the river bed level.

Analysis and investigation revealed the need for a longer approach transition and stronger section against overturning and tension for the retaining walls. River bed scour at the abutment and wingwall toe needed critical attention and treatment as well as constant surveillance for sustainable safety of such hydraulic structures.

Careful and participatory water management resulted in near optimal crop yield even for the emergent situation that resulted in 18 days of canal closure. For the command area that receives year round irrigation and with watertable 4 to 5 m below, 15% less supplementation did not affect crop yield.

Note: The first author functioned as a superintendent engineer in-charge of operation of the system (1981-1987) and was directly responsible for the restoration work. The second author is an International Training Consultant for the World Bank assisted Water Resources Consolidation Project in the State of Orissa.

NEEDS OF DRAINAGE FOR SUSTAINABLE CROP PRODUCTION IN THE SALINE ENVIRONMENT

K.K. Datta[1]

ABSTRACT

Sustainability of irrigated agriculture in the arid and semi-arid regions of the country has faced the challenge of alkalinity/salinity problems associated with soils and irrigation waters. One of the major problems confronting present day agriculture is decreasing availability of good quality irrigation water. With increasing demand and decreasing availability of good quality waters, there is growing tendency among the farmers to use these poor quality waters for crop production. Indiscriminate use of poor quality waters in the absence of proper soil-water-crop management practices poses grave risks to soil health and environment. In India about 36 percent of irrigated lands have been damaged at different levels due to such practices. This disappointing picture due to faulty irrigation development. Failure to create "enabling condition", lack of institutional support, lack of provision of drainage, all contributed to failure to prevent the growing problem of water logging and salinity. Area under canal irrigation during the last three decades was only 19 percent but area increase through tubewells has been of the order of 160 and 189 percent in Haryana and Punjab, respectively. The scenario on ground water utilisation is not the same in several other states or their specific areas disadvantaged either with poor quality aquifer yields or their quality. Surveys rate 32-84 per cent of the presently operable wells of different states to be of poor quality.

A number of technological options are available (like improve water management practices through sprinkler, drip irrigation etc (ii) conjunctive use of ground water where quality is poor, (iii) skimming well/ *doruvu* technology where shallow ground water management is needed and (iv) subsurface drainage (SSD) where water table is high and quality of ground water is

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poor) to augment the effective supply of land. Though these options are crucial, they have themselves tended to be centralized and technocratic and hence capital intensive. For such reason, each of these prescribed strategies/ remedies enjoyed the status of a 'privileged solution' at one time or other. There was no effort to harness the synergic benefits of those options, with the result that no progress was achieved in testing these strategies together. It does not stimulate testing and modification and does not promote a 'learning process' strategy. This paper mainly suggests different policy options and strategic approaches like institutional intervention through participatory approaches from technical mode to participatory mode, group incentives, price policy for different water saving devices and clear cut ownership right for sustaining crop production in saline environments of India.

INTRODUCTION

India, in pursuit of irrigation development under financial constraint, has ignored the planning and implementation of the drainage systems, the consequences of which have emerged into the waterlogging and salinity in irrigation commands. 6-mha land is affected by this problem. Northwest India, comprising parts of Haryana, Punjab and Rajasthan is a highly fertile alluvial land. This region is covered under a large network of canal commands which at present suffers from the waterlogging and salinity in pockets adjoining canals and within low lying areas underlain by saline groundwater in deeper aquifers. The shallow aquifers contain large variation in water quality from fresh to marginal and saline. The climate is semiarid and arid with low annual rainfall from 100 to 500 mm under high evaporative demands from 1600 to 2000 mm. The canal water allowance varies from 2.5 to 5 cusec per 1000 acre of irrigated land. The intensity of irrigation varies from 50 to 10 percent. The land elevation is from 50 to 240 m above sea level. Soils comprise sandy loam, clayey loam, loam and sand. Two-crop system is prominent in canal commands with wheat in rabi season (winter) and rice, cotton and coarse grains in Kharif season (monsoon) as per the water availability and agroclimatic conditions.

Salinity and waterlogging in northwest India

Floods occur in Haryana and Punjab with part spillways to Rajasthan through the inland river Ghaggar. Haryana faces the waterlogging in central and western parts in less than 2 percent area in dry season (June) which expands to 15 percent in wet season (October). Punjab faces the waterlogging in the southwestern part in 2 to 3 percent area in dry season, which increases to 20 percent in wet season. Rajasthan faces waterlogging in IGNP command in northern part in about 2 percent of stage I command in dry season, which increases to 10 percent in wet season.

The irrigation bureaucracy is constrained in responsiveness to efficient water distribution, operation and maintenance for various reasons. The outcome of these are decaying of the irrigation system, mismanagement of water and existing low crop productivity below 2 ton per ha. The pricing of irrigation water revealed that 43 percent of the operation and maintenance expenses were incurred on the irrigation bureaucracy in 1986-87 which increased to 70 percent in 1990-91. Time is not far off when the entire amount shall be absorbed by the bureaucracy on its pay packets, raising an important question as to what role farmers can play in water management, water distribution, operation and maintenance with adequate financial viability.

The inherent drawback of the institutional setup in irrigation systems is promoting irregularity, uncertainty, favouritism, exploitation and corruption. To overcome during the seventies and eighties, major emphasis was shifted towards improvement of irrigation performance through on-farm development (OFD), participation in the form of involving water users and strengthening of irrigation agencies. But there was no effort to harness the synergetic benefits of those options, with the result that no progress was achieved in testing these strategies together.

From the 90's onward, rethinking is going on to transfer of responsibility and authority for irrigation management from government to non-governmental authority. Such transfer will help the water users to maintain transparency, accountability and supporting incentives to the users by managing, operating and maintaining of irrigation system. The main draw back in the system is that it assume free market mechanisms will work implicitly i.e., well-capitalised and market-oriented farmers will take care of the operation and maintenance.

But in reality it is difficult because the inherent drawback of unsatisfactory performance of the irrigation system is due to non-fulfillment of the target, incompatible rational action with collective rationality and finally quantity-constrained behaviour compelled the individual to adjust their own private decisions. Even if the market fully reflected the values for individual goods and services, the market would still allocate less than a socially optimum amount because farms are unable to fully appropriate the gains from R&D. Without internalization of environmental externality and holistic approach, only shifting the power will not improve the system.

OBJECTIVES

Keeping in view of the above scenario, the present paper will address what form of institutional set-up is needed to take care of the drainage and irrigation system together for sustainable development of agriculture. The specific objective of this paper is to review the losses due to water logging and salinity; impact of subsurface drainage technology as a preventive/curative measure of water logging and soil salinity; why the technology is neglected and finally suggest what form of institutional set up is needed for the success of drainage technology.

EXTENT OF THE LOSSES

Several scholars have highlighted the extent of water logging and secondary salinisation due to mismanagement of irrigation. Worldwide the extent of damages due to salinisation is ranging between 36 to 12 percent. In India, the damage of irrigated area due to salinisation is more as compared to top five world wide irrigated countries (Rydzewski, 1992). In the global level the annual loss from 45.4 mha salt affected lands in irrigated area has been estimated as US $ 11.4 billion (Ghassem et al., 1995).

In India estimated losses vary in different command areas. Crop wise the pure effect of soil salinity in declining yield ranged from low level of about 3 to 1 percent for sugarcane and wheat in parts of western Yumana canal and the Bhakra system to a high level of about 74 to 64 percent for paddy and all crops in the Sharda Sahayak Irrigation Projects (Joshi et al 1995). In the Chambal irrigated command area it was about 21,000 ha (Ajmera, 1997). In Western Yumana Canal and Bhakra system the annual income losses due to water logging and salinity ranges from RS. 2455 to 3718/ha (Datta 1999). The variation of losses mainly depends on the degree of degradation of land. It is interesting to mention that farming community is still not worried about the dimension of the problem, because the severity of the problem is not uniform. Major losses due to waterlogging and soil salinity at farm level threats the sustainability of land resources, decrease the farm production by abandoning of crop production; decline in resource productivity and cut-back in resource use. At the regional level the consequences are displacement of labour from agriculture, widening income disparities and affect the sustainability of secondary and tertiary sectors. At the national level the negative effect of waterlogging and salinity are in the form of decline in agricultural production, affecting the gross domestic product, bringing down export of important crops and increased import bill (Joshi et al, 1995).

TECHNOLOGICAL OPTIONS

Various remedial measures such as better water management, conjunctive use of canal and ground waters, improvement of surface drainage, on-farm development, introduction of forestry and shallow ground water management were suggested. Increasing the ground water discharge and controlling the water table can be effective by vertical (skimming well) or horizontal drainage. In the approach paper of the Ninth Five Year plan (1997-2001), it is proposed to improve the efficiency of end-use of water through adoption of water-efficient devices and promote conjunctive use of surface and ground water. The entire attempt, which was mentioned, was present and initiative was taken for a long time, but suddenly calls for an organised solution by means of public intervention. Those solutions are not thought to require testing and modification for sustainability in long term. Attempt is always in terms of diverting fund from one specific scheme to another alternative option. However, as a preventive measure for short run, those solutions may be effective but for long term, subsurface drainage (SSD) has been proved to be the only option to reclaim the waterlogged saline lands, where salts are accumulated both in soil and ground water. In Egypt SSD is provided in 1.75 million ha of its irrigated area, in Western U.S.A 25-30 percent irrigated area is covered under SSD, Pakistan also has embarked on a big program of providing SSD in its irrigated area. Although the history of horizontal drainage in India started in 1925 at Chakanwali (now in Pakistan) and in 1928 at Baramani in Maharastra but the concept of SSD is new. It is now realised that SSD is most important component of irrigation system management to maximize the benefits from irrigation investment. The cost of installation of SSD mainly depends on soil type, depth and spacing of drains, location under drainage and the type of the drainage material used. At present (1994-95 prices) the cost of manually installed SSD varies from RS.22, 310 to RS. 18,525 per ha in Haryana (Datta & de Jong, 1997).

There are basically three reasons for installing agricultural land drainage systems: (i) for trafficability so that seedbed preparation, planting, harvesting, and other field operations can be conducted in a timely manner, (ii) for protection of crops from excessive soil water conditions, and (iii) for salinity control. It is well documented that subsurface drainage **sustains** or **restores** the productivity of the agricultural land (Datta & de. Jong 1997).

Effects of SSD on Farm Economy

The impact of SSD both in short run and in the long run are well established both at the national and international level. The success story of SSD for sustaining the farm income is well documented in Holland, Egypt, Canada and Western part of USA. At national level, impact of SSD is yet to be established. In Chambal command area about 10 thousand ha is under SSD. In Haryana, SSD was installed in 589 ha at thirteen different locations in different years in order to prevent, or enable the reclamation of areas, which were already affected by water logging and soil salinity. That is why Haryana State was selected as the site of the study. Moreover, about 2000 ha in two different location has been selected for SSD under Indo-Dutch collaboration. For this paper, the study was conducted in seven small-scale drainage areas in Haryana and four in Gujarat State.

On-farm benefits of subsurface drainage enables the control of the watertable level and the desalinisation of the soils by leaching, either with irrigation water or with the monsoon rains. Operational research on Sampla Farm showed that salinity in the topsoil decreased rapidly after drainage, from about 50 dSm^{-1} in June 1984 to about 5 dSm^{-1} in November 1985, in spite of low rainfall in these years (Rao et al. 1991). In all small-scale pilot projects in Haryana State, the short-term effects of subsurface drainage were:

- A considerable increase in cropping intensity;
- A shift in the cropping pattern towards more remunerative crops;
- A remarkable increase in crop yields;
- An increase in the efficiency, or productivity of fertilisers;
- Increase in gainful employment;
- Timeliness of planting and harvesting;
- Increase the land value

The combined result of these changes was a substantial increase in farm incomes (Datta et al, 1992,Datta & Joshi, 1993, Datta & de Jong,1997).

Constraints of the Technology

In the saline environment, due to fragility, low accessibility, internal resource heterogeneity and marginality of biophysical resources, the farm families sustain themselves through adaptation to harsh biophysical environments without dependable and effective external links on extensive scale. The people have to live with limited, high risk, low productivity options. To evolve their sustenance strategies through adaptations of limited natural resources, they included seasonally and spatially diversified land base activities. Despite internal inequities and occupational specific differences in gains, everybody's close dependence on local resources created an integrated collective stake in their activities. The first and foremost condition to accept the technology depends on how far the ecological constraints accept it. Secondly it is crucial to unearth the social and institutional arrangements that determine the degree to which different groups in the society have access to the technology.

Despite yielding high dividends, collective action is required to realise the potential benefits from SSD due to indivisible nature of the technology. The study from small scale (SSD) area in Haryana and Gujarat visualises several constraints in its adoption levels (Datta & Joshi, 1993). These are (i) indivisible nature of the SSD technology, (ii) no attraction to an individual farm household on investment to prevent or cure the degraded lands, (iii) increased economic differentiation and socio-political factionalism and (iv) internal heterogeneity and inequities. The technical and economic issues relating to curative or rehabilitation of land in the saline environment depends on its productivity. Evidence shows that people care more about a more productive unit than unproductive unit.

Reconciliation of interests of divergent groups is foremost for the success of SSD. There are several factors determining the success or failure of people's participation in effectively implementing drainage activity (Datta & Joshi, 1993). These are (i) problem of "free riders", (ii) degree of participation of beneficiaries, (iii) conflicting objectives, (iv) perception of the program objectives, (v) factionalism in the village, (vi) high dependence on government patronage and (vii) completely eroded culture of group action and sharing systems.

To overcome such problems a 'weakest link ' (i.e. public output corresponds to the minimum of the outputs selected by participating farmers) is needed to establish what will work against free riding. Policies are needed such that intervention could alter the process through which each farmer experiences the effects of others so it corresponds to a ' weakest link ' technology in its effects on each participant. Mechanism to build-up the 'social capital' for promoting trusts, sharing and group action is needed. To make such social awareness and mobilisation, grassroots level voluntary agencies complemented by genuine encouragement by the state are needed. A number of participatory rural development initiatives are already in place (Krishna et al, 1997, Zazueta, 1995). To replicate such success stories in the SSD area may be the effective approach to equip the farmers to manage the SSD and build collective stake.

Participation of beneficiaries is widely accepted as the key for successful management of the drainage activity. The higher the degree of participation of the affected population, the greater will be the success. It has been realised that mere planning and executing the drainage systems to manage saline and water logged soils by a government agency may not yield the desired results unless there is a positive attitude and strong will of the beneficiaries to participate in the programme. If the conception, design and implementation of external intervention like SSD is not clear at the grass root levels, then such intervention will finally lead to dis-empowerment of the communities, disintegrate the community stakes and marginalise the local knowledge system and institutional arrangement. From the study for Haryana and Gujarat, it suggest that persuasion, education and demonstration of the beneficial role of farmers' participation is crucial for the successful operation in managing such type of problem soils (Datta & Joshi, 1993).

Differential resource endowments mainly created the incompatibility of rational individual actions with collective rationality. Any kind of formal or informal group approach to manage problem soils will have to assure each individual participant that decisions of other individuals will not cause any negative externality. But a major problem arises when all villagers do not subscribe to similar use or same product from SSD. For instance, the large farm size group wanted to grow paddy whereas the small or marginal farm size groups prefer to produce jowar for their livestock. Rice growing farmers blocked the lateral to maintain the moisture in the paddy field. On the other hand the tail-ender of the lateral block of SSD farmers did not wish to maintain such moisture in their field. For such reason a differential crop-mix in a drainage area lead to conflicts amongst the beneficiaries. Achieving higher efficiency of the investment in drainage to control salinity and water logging can solve it.

WHY ORGANISATION IS NEEDED?

To get sustainable benefit from any biological systems, management interventions are must. For the success of management of natural resources (mainly land and water) the involvement of local people is essential. This is because the use of natural resources by any user has many unintended side effects, called externalities, on other co-users. Adoption of soil water conservation measures requires the participation of all owners irrespective of whether they are owned privately or publicly. Because of interdependency, it called for co-operation of all the resource users for minimizing the externalities involved. The point of concern is not a questionof integration and its benefits but its process. It has already been mentioned in the earlier section that the loss of traditional arrangement is largely as a consequence of specific approach to integration and development. For instance, poor mobility and internal heterogeneity of resources in the saline areas focused on centralization and intensification instead of high degree of decentralization and diversification. The incorporation of community stake, local control and functional knowledge of SSD are the essential components of sustainable crop production in the saline environment.

There are many good reasons for the involvement of farmers in the development works. It is no longer possible to burden the Government organisation with such works, which are beneficial to the people, and so let people be responsible in the execution and their maintenance. In view of liberalisation and privatisation people are expected to assume greater role and share the cost of such development works. The capacity of farmers to contribute to capital, operational and maintenance expenses (O& M) in the post drainage developmental phase was explored. This could only be accomplished meaningfully by involving the farmers right from the stage one, i.e. in planning, design, construction and operational phases. As it has been mentioned earlier that irrigation and drainage works are collective in nature and are not divisible. In other words the SSD affects all the farmers and shared more or less equally in a drainage block. Even if one farmer objects to installation then the whole process is jeopardized. Therefore, the co-operation and consensus of farmers is needed at the planning and design stages as well. Unlike seed-cum-fertilizer technology, the success of agricultural land drainage largely depends upon the nature and extent of participation of the farmers as a group or community. In the past, there were some passing references that a formal or informal group approach has immense role in managing such soils. Community management of soil resources requires a different strategy. To prevent or cure land degradation through group approach may provide useful policy prescriptions for sustaining the productivity of land in a rapidly rising population age.

Options for Drainage Organisation

For the management of SSD, focus on bottom-up approach, sensitization of the decision-makers to local people's participation through participatory approach, identification and incorporation of rationale of traditional practices into new technological and institutional measures planned should be encouraged. The question may be raised of whome will organise farmers to come together to manage their problem soils. The task may be taken-up by the government as well as non-government agencies. A preliminary review of the institutional options for creation of drainage organisation capable of implementing large scale SSD in Haryana revels, at least five distinct possibilities.

1. The recognition/ restructuring of the Soil Conservation Office and incorporating the operational pilot drainage project nucleus organisation to undertake large scale SSD.

2. Incorporating operational drainage project into the existing Haryana Land Reclamation Development Corporation (HLRDC) or with Haryana State Minor Irrigation Tubewell Irrigation (HSMITC).

3. Creation of totally new non-governmental organisation exclusively to the implementation and monitoring the SSD.

4. Creation of new department of agriculture which will solely be charged with reclamation of wastelands, where operational drainage project will work as a nodal organisational unit.

5. Creation of drainage co-operative like *Pani panchayats* in Maharashtra may be another form.

In brief three general directions for long term establishment of a drainage organisation appear plausible, placing it in a governmental context or a non-governmental organisation or an incorporated public enterprise environment. To recognise government agency seems pragmatic because of the pressures to minimize expansion of the public sector generally. But scaling up the existing drainage staff from department of agriculture, to a level sufficient to meet the challenges of large scale SSD could be accepted since this would be a budget neutral solution, consistent with the policy of restraining growth in the public sector.

Involvement of some Non Government Organisation (NGO) was recommended in order to mobilise and seek participation of farmers with a view to cover larger drainage area. The major constraints of NGO's are non-existing in such a system in Haryana, an out-side NGO has its own problem of communication, lack of accountability on the part of NGO, lack of knowledge of SSD, understanding the nature of the problem, and getting access to different interests groups for developing strategies to evolve solutions.

Other alternative is in the form of drainage co-operative like in Gujarat, which was registered as 'Saline land agricultural development Co-operative' in 1989-90 under the Gujarat Co-operative registration Act of 1860. The main activity of this co-operative was to share O& M cost. Widening the activities of drainage co-operative is essential for its sustainability because the need for soil improvement will not be uniform in the entire drainage area. The farmers located in disadvantageous position may not be enthusiastic to participate in such co-operatives in the long run (Datta & Joshi, 1993).

Place the Haryana Operational Pilot Project (HOPP) in the semi-governmental corporation: This could be accomplished by either creating a new organisation with exclusive mandate for large scale mechanized SSD works or to integrate the same into an existing corporate entity as HLRDC or HSMITC. A move in this direction would potentially have advantages over the government locus. But its success mainly depends on commitment and motivation of the staff.

Approach to Set Up for SSD

Since participation, power and well being are the key factors for the success of any technological intervention, bottom-up and countervailing actions by the farmers to influence decision made through direct and informal means has been given priority in Haryana Operational Pilot Project area. Participatory approach besides co-lateral relations and linkages at all level has emphasised.

The most distinguishing and striking part of SSD in Haryana is its vibrant and constant interaction with farmers, or rather all stakeholders. One entire farmers' participation section (FPS) was created just to ensure that farmers and other stakeholders developed a basic awareness about what is SSD, what are waterlogging and salinity, what are their pernicious influences and design of works. A very well defined system of mass awareness coupled with gender focus was developed through FPS section. Farmers have been sensitized and enlightened about SSD. This section is always in touch with the village Sarpanch. FPS section also developed good rapport with the progressive farmers, key and effective persons in the villages in order to settle any disputes arising during the process of installation of drainage who has good rapport with the villagers. Parallel Women's informal organization was emphasized.

Farmer's participation is based upon bottom up, decentralized, democratic, strategy in which farmers have the sense of owners of the drainage system. Flexible and learning approach to inculcate their maximum participation and interaction at every stage, consensus and co-operation of farmers is also essential to keep the construction process smooth. Their co-operation also contributes to reduce the conflict during construction. To keep in such spirit it is decided consciously that the component of crop compensation need not be perused in view of the large-scale implementation of similar projects in the state. This policy decision helps to check the farmer's opinions about the involvement in the scheme. For accomplishing this task, farmers' participation supported with the consultants was created in the project as an important wing.
In the FPS section the important role of the Community Organiser and Women mitigators in conflict resolution,

when drainage block farmers are resistant during field construction activities. It also works as a second-line defence for Farmers' Drainage Society (FDS). FPS section acts as an interface between farmers and the project. To motivate and for mobilization a written agreement is also done with all farmers on a drainage block basis. Farmers realize that major beneficiaries would be those landowners who are covered under SSD. Drainage Block of about 50 ha was made in order to maintain optimum group of persons. Since larger groups, higher the transaction costs of bringing them together, and hence the higher the tendency of free rider. In order to avoid it, the number of farm families kept in a group is quite small. The number of farm families in FDS blocks ranges between 30-35. The societies are registered under Societies Registration Act 1860 under Section 21.

The main objective of the FDS is to take care of operation and maintenance of the SSD system. There are about 22 FDS blocks planned in 1000 hectare (of saline waterlogged area) in Gohana. The preliminary task of each block of the FDS is to de-watering the initial drainage saline water (effluent) from the sump. Accordingly they have created their own bylaws so that the group's activities address the felt needs of the group members. The group has enough solidarity to compel other people and organisation to cooperate with them in addressing the group member common needs. FDS tend to be strongest when they (i) collect members' monthly or yearly fees in order to strengthen the financial position of the society; (ii) the members of the society should give time as and when it is needed for the success of the group (FDS); and (iii) provide credit facilities to their members through a carefully planned, mutually accountable credit programme.

Already about 14 such societies are registered and functional. The operation for de-watering was initiated through those societies. At present about seven such cooperatives are operating smoothly for initial de-watering. Mid Term Review of the project observed that participatory aspect is encouraging and turnover of the operation and maintenance responsibilities to farmer's societies. In fact the effort is mainly to break down the old culture of dependence on public sector subsidies. It has to be careful to find out tailoring solutions to this fiscal challenge by the FPS per the site conditions of different drainage blocks in the area. FDS require common funds to prolong the O& M works on a sustainable basis. The effectiveness of first drainage Block is precedent for the subsequent efforts made in this direction. It is a learning process and must be stepped up systematically. An apex body of all the FDS is to be established to co-ordinate and pull the experiences at the project level.

It must be mentioned here that as the construction work of SSD accelerates the workload of the FPS increases. At present this section is motivating, collecting construction consent signatures, conflict resolution, organising and registering FDS's. Too many activities forced the section to thinly spread to follow up and support the FDS. The vitality of the FDS's will mainly depend upon considerable follow up required by the FPS with each FDS. At present the turnover of SSD systems to the farmers (FDS) appears to be on an informal adhoc basis. As the actual status of the turnover in different drainage blocks is unclear, it is imperative that a clearly defined system is needed before handing over to FDS. For instance in FDS block 12, even though installation of SSD was complete for a long time but still the pump set for de-watering is not functional and there are no clear cut guidelines for passing the drainage effluent. Similarly in FDS block 13, the surface drainage through which effluent passes is not enough. Overflowing the saline effluent drainage water spoiled the paddy crops during 1998 to the nearby farmers' field.

In FDS block 14, due to negligence of supervising role and management, de-watering activity is neglected even though record shows that the expense for pumping is going on. There is much malpractice going on even though the village Pradhan who is also the president of FDS block 14 appoints pump operator. In order to remove the stagnant water from the (matured) paddy field, pumping for de-watering is needed to bring confidence to the farmers in FDS block 7 but such activity is not taking place due to some technical fault of the pump. There is much seepage of canal water directly to the sump, reducing the confidence of SSD technology in the farmers. It is essential to solve such problems immediately before taking up new areas for drainage installation. Unless a fully operational SSD system is provided, farmers will be hesitant to cooperate with O& M of FDS. Success of FDS primarily depends on the strong determination and commitment of the project personnel authority to demonstrate exceptionally good performance and to solve farmers' problems regarding water logging and soil salinity in their field.

Alternative to Farmers' Drainage Societies i.e. involving of some Non Government Organisation (NGO) was recommended in order to mobilise and have participation of farmers with a view to cover larger drainage area. In the process, NGOs may not only focus on selling their own perspectives and approaches but tend to build their own space and indispensability that will help the state, which neither understands the rural communities well enough nor can deliver promised goods and services.

Whatever may be the form and its nature, drainage requires huge investment. In addition to that O& M cost is needed. Unless such costs are recovered from beneficiaries, the state has to incur large subsidies. Since drainage technology is indivisible in nature, to an individual farmer adopting the technology in isolation is financially non-viable. It requires certain institutional arrangement. The issue is whether drainage will be treated as public well or private.

In any case farmers should pay the operation and maintenance cost, because:

a). it would assure the sustainability of the project;
b). it would give the farmers the sense of ownership and responsibility;
c). it would alleviate the burden on public exchequer.

In view of the modest return on drainage investment and the limited repayment capacity of the beneficiaries, the question is whether to drain or not to drain. It is clear that the farmer cannot bear the full burden of the cost of drainage. But, since the deterioration of valuable agricultural land has to be controlled for the sake of farmer and the society as a whole, land drainage is a joint responsibility of the Government and the farmers. The arguments for this are:

i). Land is needed to feed the growing population;
ii). Good agricultural land is scarce;
iii). Irrigated land is highly valuable;
iv). The cost of drainage is only one-third of the cost of irrigation;

v). Waterlogging and salinity are partly due to the farmers;
vi). The damage is unevenly spread over the farmers' land. It is externality for the affected farmers;
vii). Large-scale soil salinity causes social disruption;
viii) Large-scale salinisation is a threat to the environment;
ix). Proper drainage is beyond the financial capacity of the farmers.

As conservationists all over the world advocate, the required return on the invested capital for conservation and environmental protection should be lower than for other investments, say 6 per cent. In that case subsurface drainage projects would become economically feasible before the land is seriously affected and farmers suffer great income losses.

PROFILE OF THE DRAINAGE SOCIETY AT HARYANA

Particulars	***Description***
Name of the Society	Farmers Drainage Society
Registration Act	State co-op Registration Act, 1860.
Area of operation	saline and waterlogged area belonging to the farmers of Farmers Drainage Society Block
Objective	i) regulate the pumping of the saline water and discharge the effluent from the outlet to the main drain; ii) Operation and maintenance of SSD system; iii) To raise resources through collection from the members for meeting the O& M cost; iv) To arrange loans, subsidies, grants etc. for the society toward reinvestment in the development of SSD, agricultural productivity and reclamation of saline soils;

	v) To take any official and legal action deemed necessary to achieve the above mentioned objectives
Aims	1. Increasing agricultural production and reclamation of saline land, 2. Adoption of improved methods of water and land management, 3. Monitoring the ground water level; quality of land and water and crop yields, 4. Reuse of the effluent for irrigation, 5. Involving women of the member households in the management and functions of the society,
Membership	Farmers, both men and women, who own or have land under their control under the jurisdiction of the Society and their spouse, above 18 years of age and sound of mind are eligible for membership, Members have to pay non refundable fee of RS. 21/-, Farmers and their spouses who lose possession of land automatically cease to be members, The ADO (Soil Conservation) of the respective area shall be the ex-officio member of the society.
General Body	All members together constitute the General Body and any decision of the General Body is binding and final, The General Body has the power to prepare and amend the bylaws, An annual meeting of the Society will be conducted during September every year. Special meetings can be

convened whenever need arises. At least seven days notice will be given for holding the meeting,

To pass proposal for amendment of the bylaws, vote of at least sixty percent of all members present is required.

Executive Committee

The general Body will elect at least seven members to the Executive Committee for one financial year,

The ADO from APO office will be ex-official member of the society who will be responsible to check the registers and other records maintained by the society,

Funds

Funds can be raised by the Society for its functioning in several ways, such as :

1. Membership fee, annual fee, or land fee;
2. Proportion of crops;
3. Fines;
4. Donations from well wishers;
5. Loans from banking institutions, etc.
6. Funds from HOPP, Govt. and other agencies,
7. The Functioning of the society will be on a no-loss and no-profit basis.

Relation to HOPP and Government

HOPP-Dept of Agriculture Haryana Officials shall have the right to verify the records and accounts of the society at any point,

On the dissolution of the Society, all its assets and liabilities shall vest with HOPP-Dept. Of Agriculture Haryana

The society is registered under the societies registration Act, 1860 and all provisions of the said act are applicable to the society.

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RECLAMATION OF TABRIZ PLATEAU

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ABSTRACT

This paper presents the key elements of reclamation of Tabriz plateau at east side of Lake Orumiyeh, in East Azerbaijan, Iran. The plateau consists of approximately 230,000 acres (92,600 hectares) of land with saline and saline-alkali soils. The sources of water include surface and ground water. The major watershed draining to the area is Ajichai basin. Ajichai originates from Sabalan Mountain, travels approximately 168 miles (270 km), and falls through 1,887 feet (575 m) and joins the Lake Orumiyeh. Along its route, various tributaries that originate or pass through salt mines join the river and consequently make it saline for irrigation. The reclamation project consists of dealing with sources of salinity for surface water and reclamation of the saline soil in the plateau with due consideration for impact of the project on Lake Orumiyeh. The project features include construction of a series of earth dams, including an impermeable earth core rockfill dam as the main storage and flood control reservoir, water conveyance facilities, drainage systems, and soil amendments. Due to salt transport in irrigation water and its commutative effect on agricultural lands, it is believed that the complex issues of this reclamation project are good examples of the nature of challenges facing irrigation and drainage in the new millennium.

INTRODUCTION

The growing need for land and water for production of food demands well planned utilization of these resources with due consideration to their sustainability. While the issue of sustainability may not have been a prevailing parameter in the past, it certainly appears to be the most important one in the future. Technological advancements of the twentieth century accelerated the use of natural resources. There have been cases where the human awareness of preservation of natural resources has grown parallel to the fast pace of natural resources utilization, and there have been cases where such awareness has lacked significantly. Nevertheless, so far, the vast resources of the earth had been capable to maintain the balance. This may not be the case anymore; i.e. nature may not be able to continue balancing itself without serious consequences to

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humankind, unless we implement serious changes, leading us toward higher level of sustainability.

PROJECT SETTING

Tabriz plateau is located at east side of Lake Orumiyeh, in East Azerbaijan, Iran. The plateau consists of approximately 230,000 acres (92,600 hectares) of land with saline and saline-alkali soils. The area is approximately 4,265 feet (1,300 meters) above sea level. Average annual precipitation is 10 inches (250 millimeters) and potential evapotranspiration is estimated at 37 in. (930 mm). Therefore, the area is arid. The land is generally flat with moderate slopes towards the lake. The soil consists of alluvial sediments with fine to medium texture. Soil permeability ranges from medium to low. The quality of ground water is good near the foothills but its level of salinity increases as it approaches the lake. The lake water is highly saline.

The pre-project agriculture is along the perimeter of the plateau near foothills where the salinity of ground water is low or tolerable. Traditional agriculture covers approximately 1/3 of the area where ½ is irrigated by groundwater and ½ by surface waters. The primary watershed draining to the area is Ajichai basin (Fig. 1). Ajichai originates from Sabalan Mountain, travels approximately 168 miles (270 km), and falls through 1,887 feet (575 m), and joins the Lake Orumiyeh. Along its route, various tributaries that originate or pass through salt mines join the river and consequently make it highly saline for irrigation. Nevertheless, during the wet season the salinity of Ajichai is decreased and its water becomes suitable for irrigation, where, to some degree, it is utilized for traditional agriculture, by river-flow diversions using low weirs into canals.

The complexity of the project stems from the fact that the prime elements of it, i.e., the land and water resources, both require careful reclamation measures in order to support a sustainable development. Moreover, the suitable dam sites for storage reservoirs and routes for water conveyance are complicated by either seismotectonics, or major saline areas scattered throughout the river route. Primarily for these reasons, some earlier attempts dating back to the 1960s were aborted with no material outcome.

Notwithstanding the earlier piece-meal studies, none of which could warrant a sound conclusion, in 1990s the East Azerbaijan Regional Water Authority (EARWA) undertook a series of systematic studies to explore the feasibility of development of water and reclamation of Tabriz Plateau. The initial phase of investigations consisted of reconnaissance studies including meteorology, hydrology, agriculture and geology of the area, and prospect of construction of dams and irrigation systems. The results of these indicated that the Ajichai basin including Tabriz Plateau has a large potential for irrigated agriculture. Further

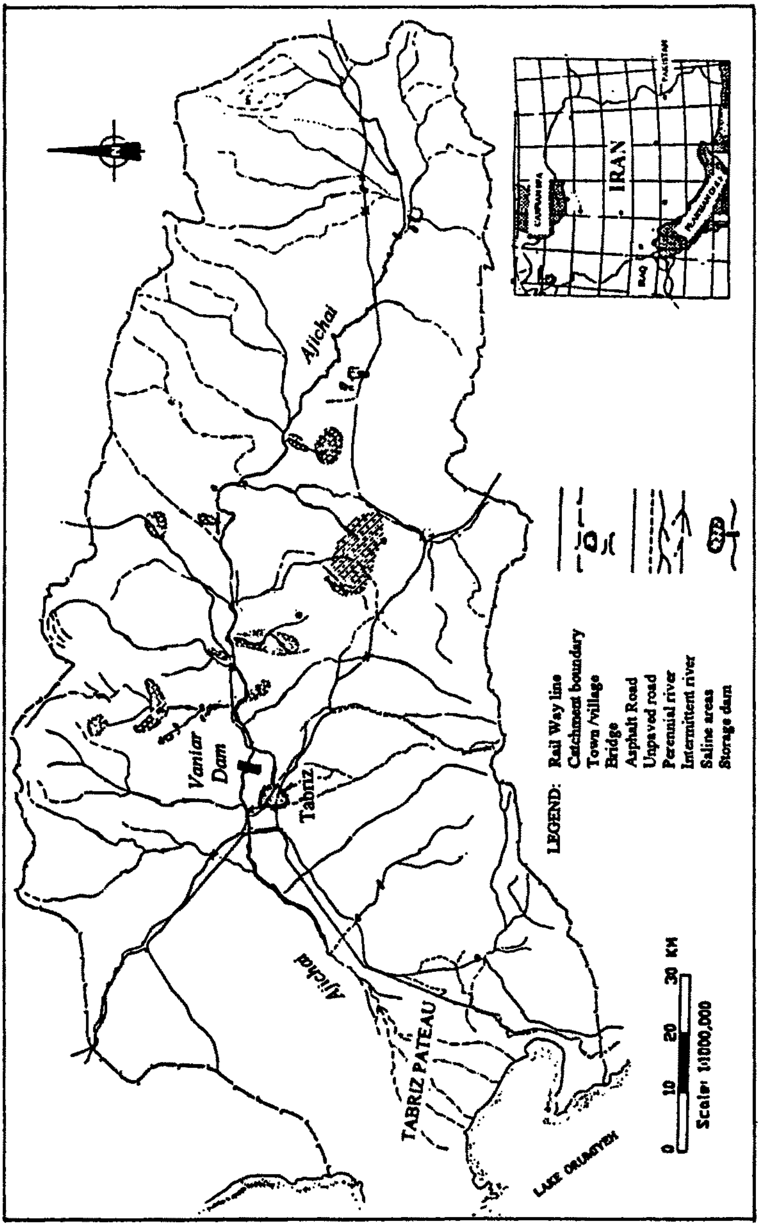

Fig. 1.- Ajichai River Basin and Major Saline Zones above Vaniar Dame Site

investigations were initiated to study the soil characteristics. Presentation of approaches taken for design of dam and appurtenant structures is beyond the scope of this paper. The highlights of these studies relative to the quantity and quality of water, soil characteristics, and irrigation and drainage principles in connection with reclamation of Tabriz Plateau are given in the following sections.

HYDROLOGY OF WATERSHED

As mentioned earlier, the primary watershed draining to Tabriz Plateau is the Ajichai basin. The highest elevation of upper catchment is 11,000 feet (3,352 m) on the south-western slopes of Sabalan mountains, which sharply drops to about elevation 6,000 feet (1,828 m) and travels a distance of about 173 miles (279 kilometers) and joins Lake Orumiyeh at elevation of 4,183 feet (1,275 m), (Fig. 2).

The average annual precipitation ranges from 10 inches to 18 inches (250 to 450 millimeters) within the watershed as indicated in Fig. 3, isohyetal map of the basin. The mean annual run-off of the basin is about 373,697 acre-feet (461 million cubic meters), based on forty years observed flow data. About 80% of the flow occur during the period of February to June, i.e., during four months, and 20% in the balance of the year, where the irrigation season in the area is between June and September. Please refer to Figures 4 & 5 for river flow variations. Such a major disparity requires some means of flow regulation, such as a dam. For further characterization of the river flow it should be mentioned that, depending on the time of the year, the river flow may range from zero to 13,450 cubic feet per second (0 to 381 cubic meter per second). However, based on a flow duration analysis, 50% of the time the mean daily flow in a typical year may equal or exceed 636 cfs (18 cm/s).

A dam site was selected near Vaniar as shown in Figure 1. Because of proximity of this site to an active fault, a rockfill type dam with impermeable earth core was selected for the project. Rockfill dam is more suitable for seismically active areas.

QUALITY OF WATER DEVELOPED IN THE WATERSHED

The primary source of surface water for the project area is Ajichai River. This river originates from the mountains with fresh water but is seriously degraded by saline reaches along its route and tributaries from saline springs, originating from salt domes or saline ground water (Fig. 1). Under such condition, the salinity of the river is in reverse proportion to the amount of flow and its Total Dissolved Solids (TDS) generally range from 1,100 PPM to 3,000 PPM in high flow season, and 3,000 PPM to 4,600 PPM in low flow season. Due to contamination by

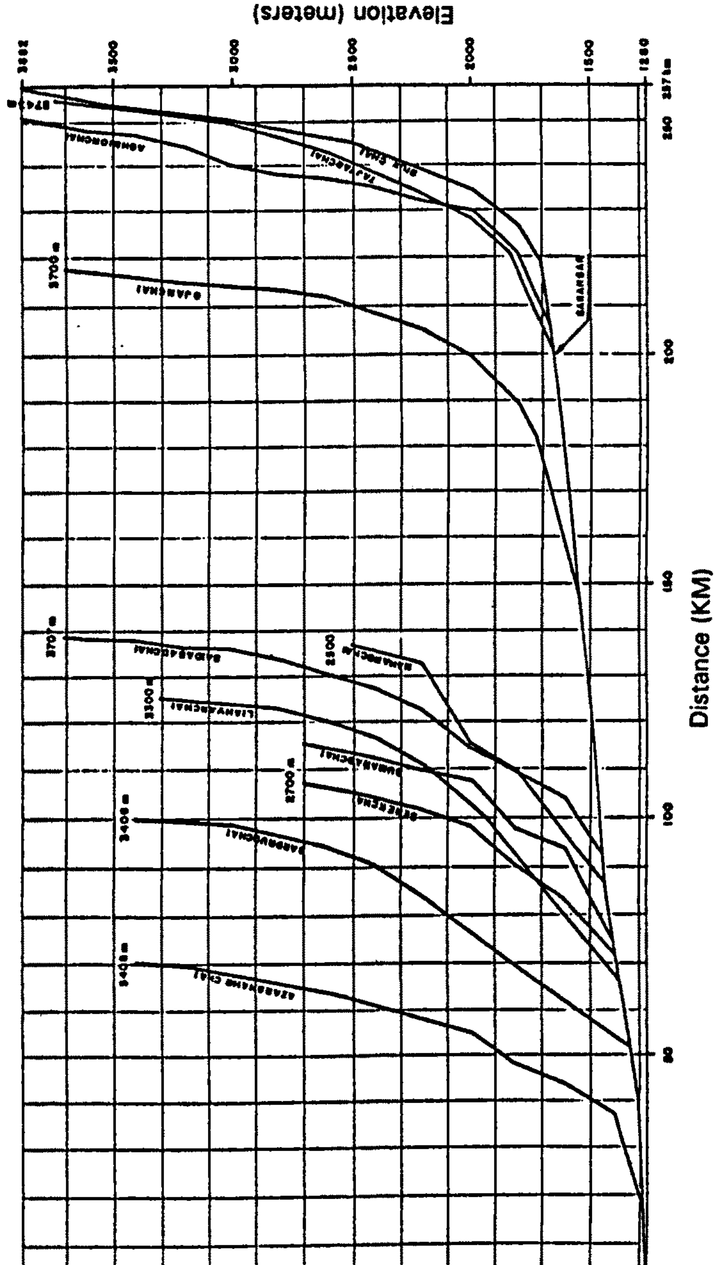

Fig. 2.- Profile along Ajichai, and its tributaries, to Lake Orumiyeh

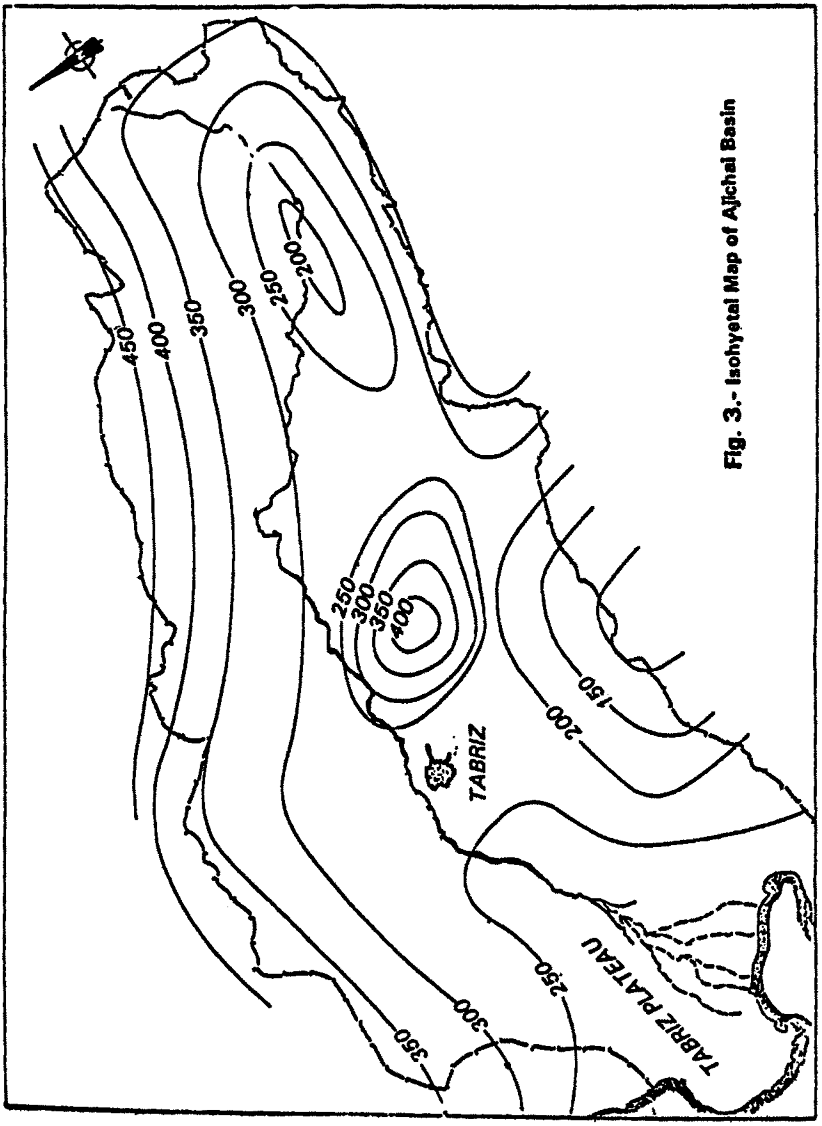

Fig. 3.- Isohyetal Map of Ajichal Basin

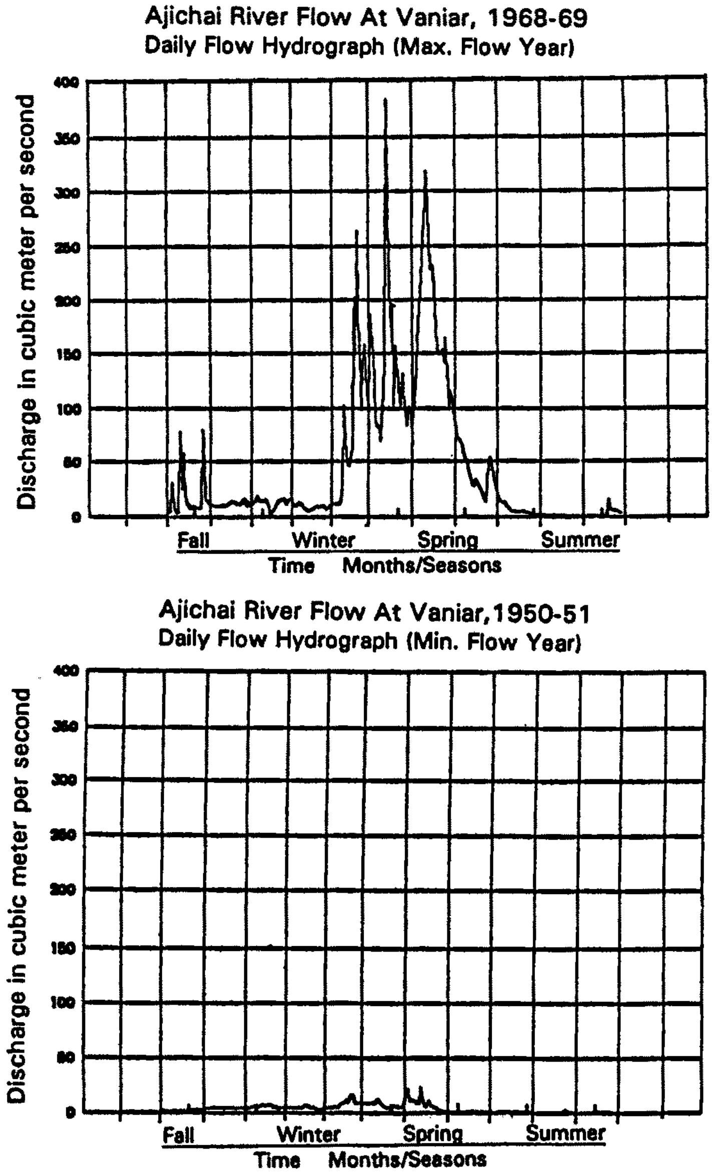

Fig. 4.- Flow Variations in Ajichai River Basin in Wet and Dry Years

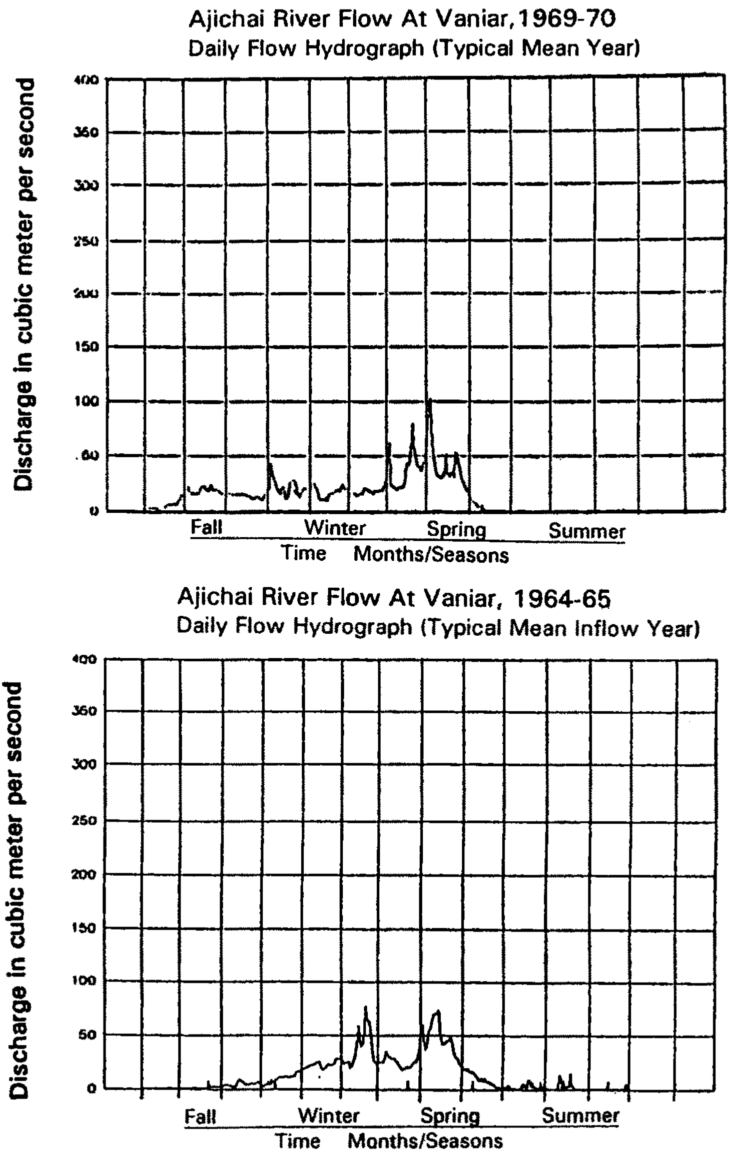

Fig. 5.- Typical Flow Variations in Ajichai Basin

brine, the Electrical Conductivity (EC) of the river for flows above 1,400 cfs (40 cm/s) is about 2000 micromhos per centimeter, and that of flows down to 350 cfs (10 cm/s) is about 5,000 micromhos/cm (Fig. 6). The Sodium Adsorption Ratio (SAR) for flows above 1,800 cfs (50 cm/s) is about 10; and for flows below 175 cfs (5 cm/s) it rises to about 20.

The quality of river flow under the above conditions was not found suitable for irrigation. Therefore, various alternatives were considered to control the effect of saline reaches and brine tributaries on the quality of Ajichai River. These alternatives included:

1) Capture of Ajichai flows in a storage dam during the period of high flows and diversion of its flow to downstream during the low flow season,
2) Isolation of saline tributaries and conveyance to downstream of project limit,
3) Considerations were also given, though implicitly, to collection of fresh water in upper catchments and conveyance to a storage reservoir using aqueducts,
4) No project and status quo.

Alternative 2 was selected because the number of reaches and the magnitude of flows were smaller making them more suitable for storage and conveyance to a discharge point in Lake Orumiyeh, with due provisions for protecting the environment. To accomplish this objective various dam sites were identified in the basin as shown in the Figures 7A and 7B. The brine water originating from salt domes will be conveyed to storage dams and eventually to a disposal site at its natural destination, Lake Orumiyeh. This brine water will be diluted before discharging to the lake. At present time, development of criteria for discharges to Lake Orumiyeh is under investigation. One potential source of water under consideration for dilution is the reclaimed water from the wastewater treatment plat of the City of Tabriz (population 1,000,000).

One of the objectives of the reclamation project is to develop water with a salinity level acceptable for irrigation. Therefore, based on economy crops suitable to the area, a goal was set to develop water with EC in the range of 800 to 1800 micromhos/cm and SAR below 10. This level of salinity may result in less than 25% reduction of the yield of the least tolerant plants planned for the area, such as field, vegetable and forage crops. The goal is achievable by isolating saline waters by means of the dams and conveyance facilities mentioned above.

Groundwater also will be used in conjunction with surface water for irrigated agriculture.

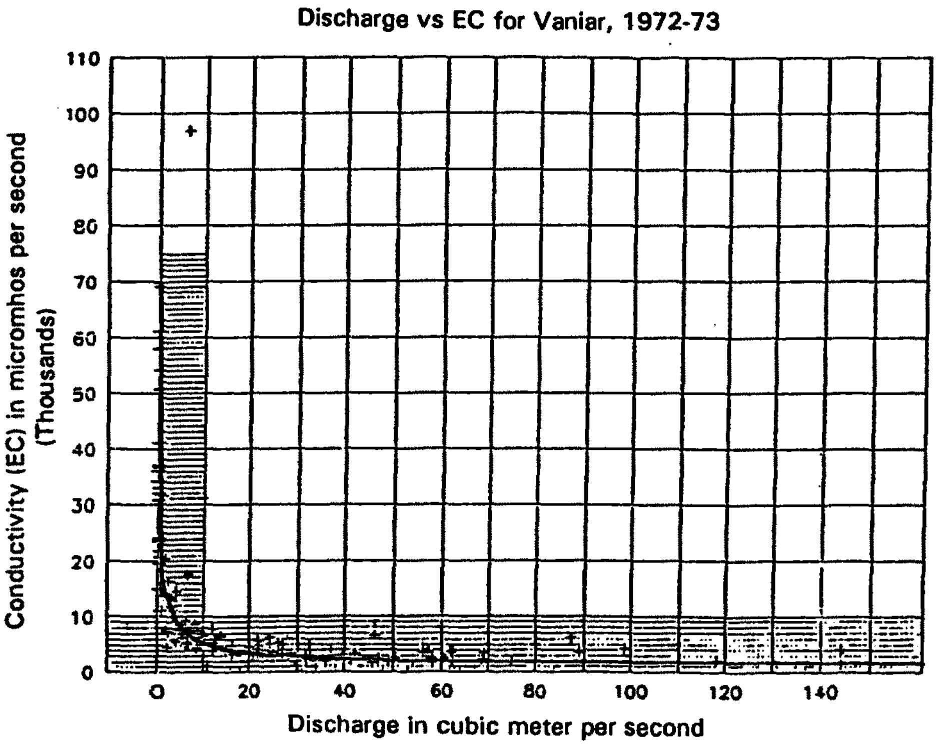

Fig. 6.- Discharge Vs Electrical Conductivity in Ajichai River Basin at Vaniar

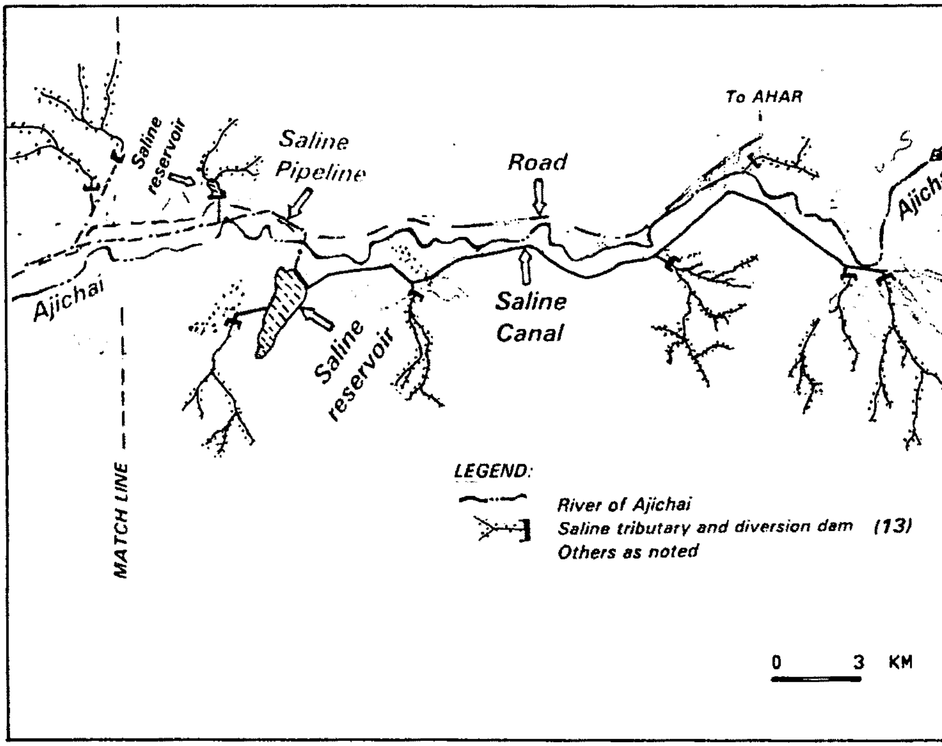

Fig. 7A. – Primary Dam Site at Vaniar, and Various Small Dam Sites for Storage, and/or Diversion, and Conveyance of Saline Waters

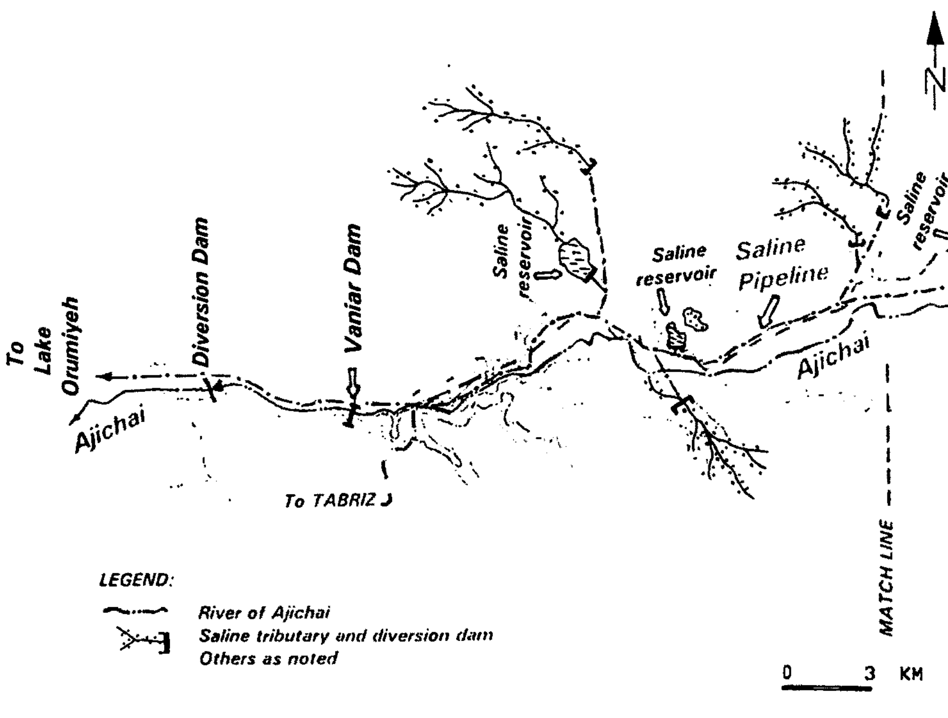

Fig. 7B. – Primary Dam Site at Vaniar, and Various Small Dam Sites for Storage and/or Diversion, and Conveyance of Saline Waters

CONSIDERATION OF QUALITY OF WATER RELEASED FROM VANIAR DAM

It is anticipated that despite isolation of brine water sources from Ajichai, the overall quality of the flow in the river may vary during wet and dry season of the year. This situation may affect the quality of the water at various levels in the main storage dam for irrigation water. A hydrodynamic investigation using computer models is underway to determine the most favorable manner to release water from the reservoir.

WATER CONVEYANCE SYSTEM

A diversion dam was planned downstream of the main storage dam at Vaniar to divert water from Ajichai to the irrigation sites on Tabriz plateau (Fig. 7B). Two main canals, which will be concrete lined, will take the water from this diversion dam and will convey it to the east and west sides of Tabriz plateau (Fig. 1). A series of secondary and tertiary canals will distribute the water to the planned farmlands. The secondary and tertiary canals also will be lined to reduce conveyance loss and avoid affecting the high groundwater table which itself is a problem, as discussed later in this paper. Furthermore, a conveyance system consisting of open channel and pipeline will convey saline waters from storage reservoirs and discharge it to Lake Orumiyeh.

LAND QUALITY AND SOIL CLASSIFIFICAIONS

The topography of the land in the planned irrigated area is excellent for agriculture, provided necessary reclamation measures to remove salt and lower the high water table. In this regard, EARWA initiated detailed soil studies and classified the soils of the irrigation project site. Generally speaking, the land is composed of alluvial sediments. The soil is very deep. The majority of the land consists of soil with medium texture. A relatively small portion of the land has fine texture. Correspondingly, the infiltration rate also ranges from medium to low. Approximately 1/3 of the land has low saline soil, which consists of the land near perimeter of the project area. Another third of the land has saline-alkali soils, comprising the majority of the land for the developed area. The last third of the land is saline-alkali with very high groundwater table. This last portion of the land consists of the area at vicinity of the Lake Orumiyeh. The efforts of reclamation are concentrated only on the 2/3 of the land with saline and saline-alkali soils, as described above. The boundaries of project area are shown in the Fig. 8.

GROUNDWATER AND SOURCE OF SOIL SALINITY

In connection with this project, EARWA conducted a study on groundwater in the project area. The general direction of the groundwater flow is from the foothills toward the lake, as one would expect (Fig. 9). The quality of groundwater is better near the perimeter of the project where the salinity of soil is low as well. However, moving towards the central portion of the plateau and towards Lake Orumiyeh, the quality of groundwater becomes more saline.

Depth to groundwater around the perimeter of the project area is about 65 feet (20 m) and the EC ranges from 500 to 2000 micromhos/cm (Fig. 10). Again, moving towards center of the project area and towards the lake, the depth to groundwater becomes less and EC increases. In this zone, the EC ranges from 2000 to 7000 micromhos/cm and the depth to groundwater ranges from 10 feet (3 m) to 3 feet (1 m) as shown in Figures 10 and 11, respectively. This situation indicated that the primary source of salinity of the soils is saline groundwater with high water table.

Studies indicated that the salinity of shallow groundwater is higher than that of the water which comes from deep wells in the area. This fact suggests that a hard pan may be present. Further investigations are underway. In the presence of a hard pan, relief wells will be utilized to dissipate artesian pressure.

SOIL RECLAMATION MEASURES

Based on the characteristics of the soil and groundwater described above, three measures were planed for soil reclamation. These are soil leaching, soil amendments and underground drainage. Field experimentation was conducted to determine the effect of soil amendments on soil texture and infiltration rate, and determine leaching fractions. An underground drain system was planned to lower groundwater to minimum of 10 feet (3 m) below ground surface. This requirement is to minimize the migration of salt from groundwater to topsoil by capillary rise. Nowhere in the area the water will reach to 4 feet (1.3 m) from ground surface.

The water from Vaniar dam will be utilized in conjunction with the groundwater in the project area. The saline soil will be leached to remove the salt to a level tolerable by selected crops. The saline-alkali soils will be reclaimed by both soil amendments and leaching. The general slope of land in the project area ranges from 0.005 to 0.0005. This allows removing the drainage water from the area and disposing it to Lake Orumiyeh. As mentioned earlier, the groundwater flow is towards Lake Orumiyeh as well. The typical hydraulic gradient is about 0.0002.

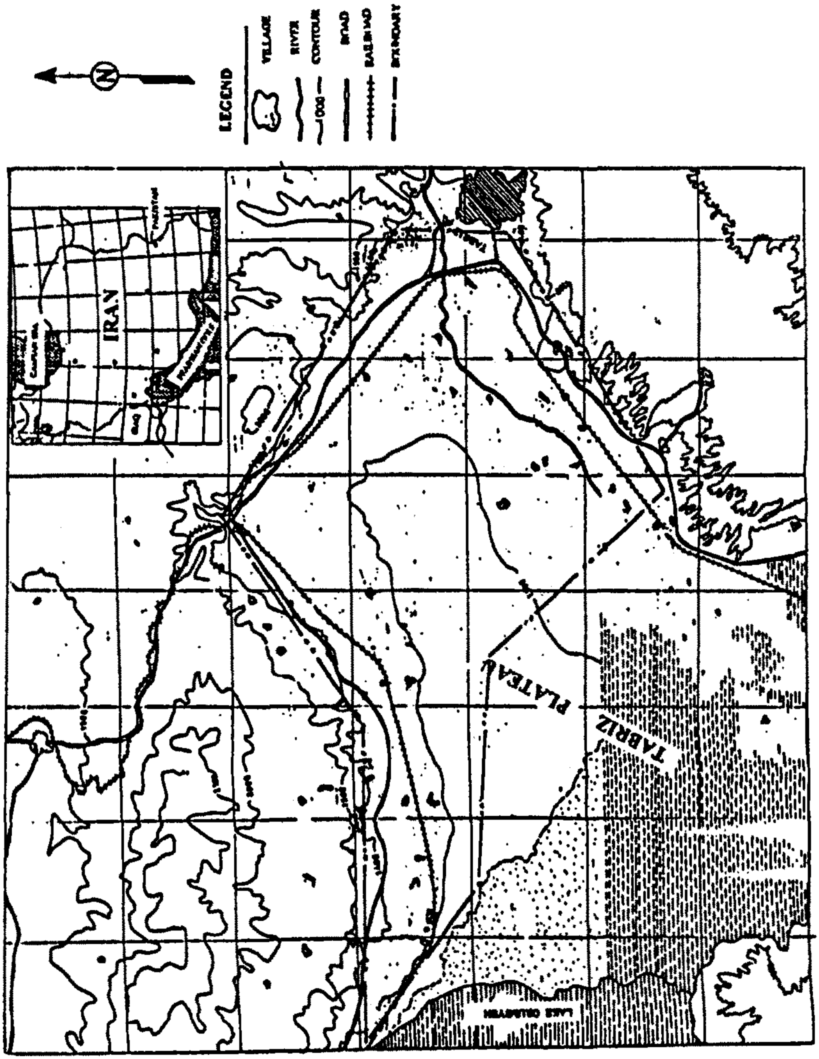

Fig. 8. – Boundaries of Project Area in Tabriz Plateau

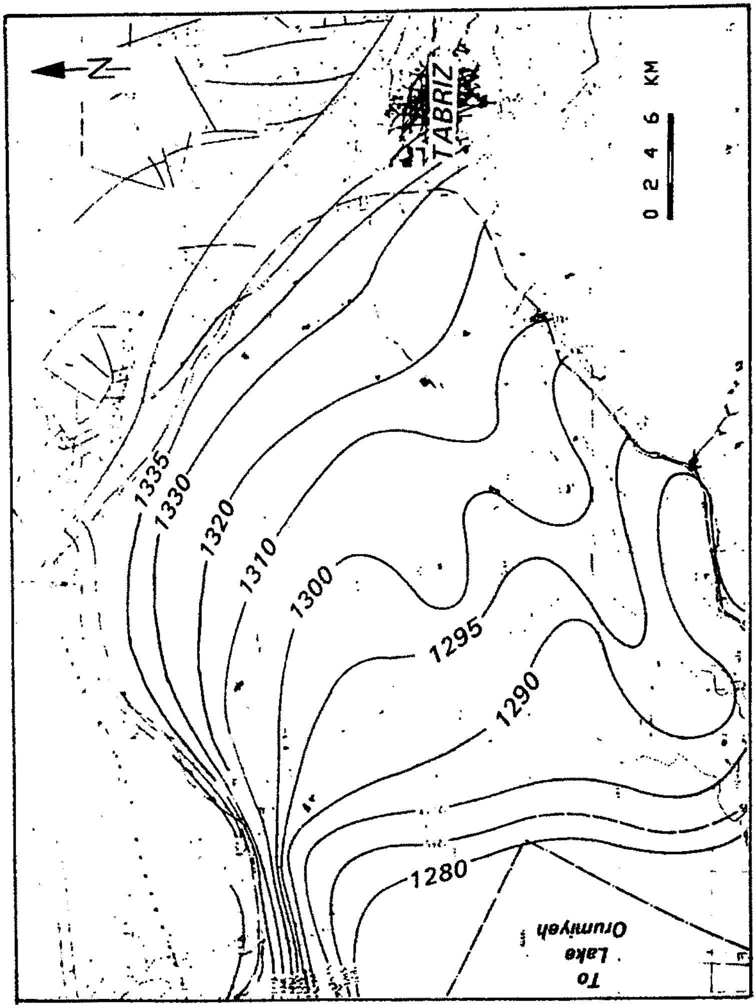

Fig. 9. – Groundwater Equipotential Lines (meters) in Tabriz Plateau

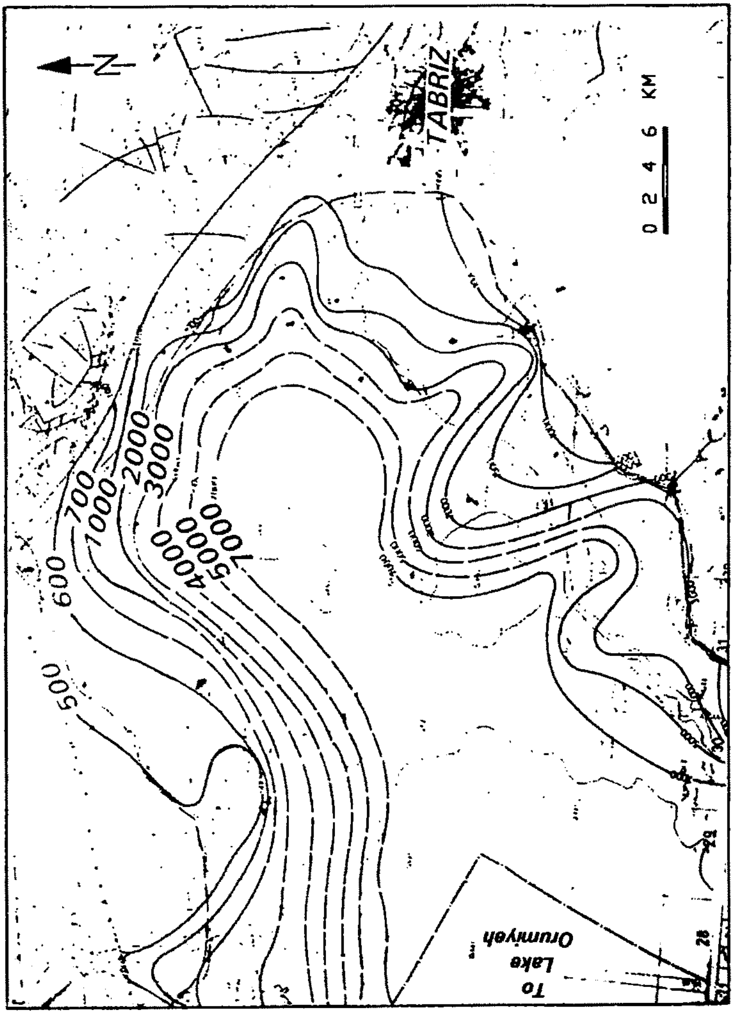

Fig. 10. - Contours of Equal EC (micromhos/cm) points in Groundwater in Tabriz Plateau

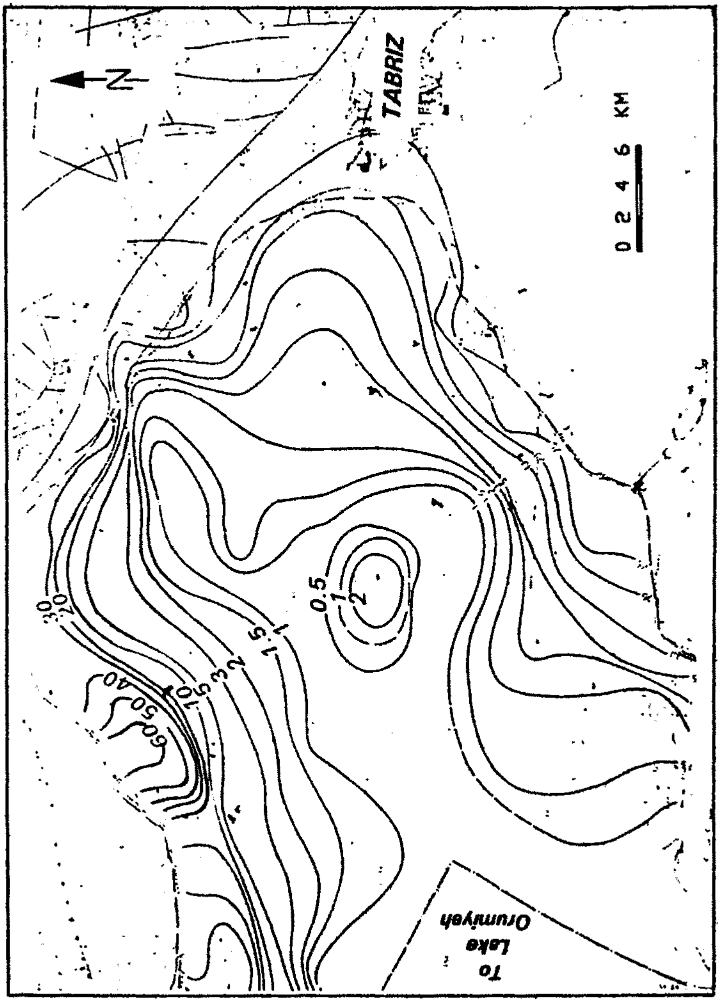

Fig. 11 - Contours of Depth to Groundwater (meters) in Tabriz Plateau

ENVIRONMENTAL ISSUES/LAKE ORUMIYEH

The primary issue of the project pertaining to environment is its impact on the Lake Orumiyeh. This lake contains a very saline body of water. Despite this fact, the discharge of brine water collected from Ajichai basin will be diluted to a level of the lake's water before disposal into the lake. Another major issue related to the subject is maintaining a fixed amount of water to Lake Orumiyeh to prevent its recession. This latter topic is being considered in a regional water plan. Various watersheds from two provinces; i.e., East Azerbaijan and West Azerbaijan are draining to this lake. The total amount of annual runoff will be maintained to offset the annual evaporation from the lake.

SOCIAL ECONOMIC CONSIDERATIONS

Approximately 25% of the land in project area are private farms with some degree of salinity problems and the water shortage. These estates will benefit from the project. Revenues from sale of water to these farmers will contribute to recovery of capital investment. The majority of the land is public land, which will be divided and transferred to private farmers; revenues from transfer of land and sale of water will be used for capital recovery.

MANAGEMENT OF IRRIGATION AND DRAINAGE SYSTEMS

The primary system of water development and delivery, such as dams and main canals, will be operated and maintained by the EARWA. Management of on-farm irrigation and drainage systems, including secondary and tertiary canals and wells, will be under the jurisdiction of a local entity. For this reason, creation of a water district is under consideration to execute a contract with EARWA to be responsible for operation and maintenance of the system and collection of revenue from sale of water. The water district will operate based on general guidelines of EARWA but will be managed by a board of directors elected by the local farmers. The governing body of the Water District will hire a general manager for the water district, and he or she will staff the office, using the district fund. This method of management is considered a major step in the direction of improved efficiency at farm level and encouragement of competence and competitiveness in rural agribusiness operations.

CONCLUSIONS

The project is unique in its ability to differentiate a major source of water from contamination by vast sources of brine water. It also reclaims a vast amount of land degraded by saline groundwater. Moreover, it introduces an improved method of water management for rural agribusiness regions.

Continued increase in population and excessive use of natural resources have caused a decline in the quality of available resources, despite tremendous technological achievements of the 20th century. Irrigation waters continue transporting salt to agricultural lands, and in numerous cases continue causing drainage problems by rising water table. Implementing careful reclamation measures, described in this paper, is a good example of supporting a sustainable agriculture, while dealing with complex challenges facing irrigation and drainage in the new millennium.

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Data for preparation of this paper was obtained from project records of East Azerbaijan Regional Water Authority, and various site visits. The authors express their appreciation for the permission to use this data. Special thanks are due to the engineering personnel and support staff of the EARWA for the assistance they provided during the site visits.

Moreover, the authors would like to acknowledge extensive studies by a joint venture of Associated Consulting Engineers (ACE) of Pakistan and Ashenab Consulting Engineers of Iran, during the reconnaissance and feasibility study phase of the project. The work of Ghods Niro Consulting Engineers of Iran in performing the project design and their subconsultants' contributions are also acknowledged. The groundwater data for this paper is based on the studies by Kavab Consulting Engineers, and the soil salinity information is based on the studies by Yekom Consulting Engineers. Furthermore, the prompt responses and keen editorial comments of Larry D. Stephens, Executive Vice President of the United States Committee on Irrigation and Drainage were instrumental in development of this paper, and are very much appreciated. And finally, preparation of this manuscript would not have been possible without journalism skills and dedication of Anna L. Sibirtsev of DAVAR ENGINEERING, in San Luis Obispo, California.

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SIMULATION OF SURFACE IRRIGATION SYSTEM USING EXPLICIT FINITE DIFFERENCE METHOD

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ABSTRACT

A hydrodynamic model for simulating the flow in Basin irrigation system is presented. An explicit McCormack method is used for solving the governing equations. This method doesn't require any special treatment of advancing or receding fronts such as sub-grid technique. The numerical procedure accommodates for three inflow boundary conditions namely line inflow, corner inflow and fan inflow. The results are compared with observed advance and recession times for two level basin irrigation events available in the literature and two field experiments conducted by authors at WALMI, Vadod, Anand, Gujarat, India. A very good comparison of results is observed. The results for various other cases are also presented.

INTRODUCTION

Basin irrigation is the most popular method of irrigation in India. The effective and optimal utilization of water through basin irrigation system has drawn attention of irrigation as well as agricultural engineers. Conventionally, the Indian basins are level as well as graded, having considerable slope in both the directions and a low length to width ratio. Hence, the flow over both level and graded basins is two-dimensional, spatially varied and unsteady. Several mathematical models have been developed to numerically integrate the two-dimensional unsteady flow equations in open channels for various applications such as dam breach flood *(Xanthopoulas and*

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Kautitas 1976, Katopodes and Strelkoff 1978), tidal flow in estuaries *(Walter and Cheng 1979, Mader 1988, Casulli 1990)*, discontinuous and supercritical flows *(Katopodes 1980 and Katopodes and Wu 1986)*, channel transitions *(Chaudhry 1993)*, etc. These models numerically integrate the flow equations using method of characteristics *(Katopodes and Strelkoff 1978)*, finite difference *(Mader 1988, Casulli 1990, Reid and Bodine 1968, Chaudhry 1993)* and finite element methods *(Katopodes 1980, Walters and Cheng 1979, Katopodes and Wu 1986, Akanbi and Katopodes 1988)*.

The application of numerical techniques to simulation of flow in basin irrigation systems is very limited. *Akanbi and Katopodes (1988)* used their finite element technique in a model for two-dimensional overland flow. *Playan et al. (1994)* used a variation of Leap-Frog finite difference scheme for basin irrigation system. These two existing models simulate for flow over the surface during the advance phase only. Once the advance is reached, the simulation is stopped and the surface flow depths are allowed to recede. The simulation of flow during the ponding and recession phase is not performed. These modelling simplifications result, in significant errors especially in case of graded basins. *Singh and Murthy (1998)* presented a hydrodynamic model for level basins. They suggested the use of sub-grid technique to improve the accuracy.

The paper presents a computational model developed to simulate the flow in a basin irrigation system. The applicability of McCormack finite difference method to basin irrigation system is demonstrated. The governing differential equations of dynamic wave are solved using explicit McCormack the method. The initial experience with the model suggests that the implementation of the boundary conditions is very important especially while simulating the depletion and recession phase in basin irrigation. Three types of inflow boundary conditions are implemented in the model corresponding to three irrigation practices *(Playan et al. 1994)*. The capability of the models to deal with internal high spots, point or linear inlet and the flow over an irrigation field with spatially varied infiltration characteristics is demonstrated. The results of the models are compared with the field measured advance and recession times for two sets of data on level basin *(Playan et al. 1994)*. An excellent agreement of results with the field observations is obtained. The model is also used to simulate flow in basin at WALMI, Vadod, Gujarat, India. The simulation results are compared with field experiments conducted by authors.

FORMULATION

The general form of governing equations for two-dimensional flow over the basin irrigation system can be concisely written as,

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+S=0 \tag{1}$$

Where, x, y = distances along either of the sides of the basin, t = time.

For complete hydrodynamic equations for basin irrigation systems *(Playan et al. 1994)*,

$$\mathbf{U}=\begin{bmatrix} h \\ q_x \\ q_y \end{bmatrix} \quad \mathbf{E}=\begin{bmatrix} q_x \\ \frac{q_x^2}{h}+\frac{gh^2}{2} \\ \frac{q_x q_y}{h} \end{bmatrix} \quad \mathbf{F}=\begin{bmatrix} q_y \\ \frac{q_x q_y}{h} \\ \frac{q_y^2}{h}+\frac{gh^2}{2} \end{bmatrix} \quad \mathbf{S}=\begin{bmatrix} I \\ -gh(S_{ox}-S_{fx})+\frac{q_x}{h}\left(\frac{I}{2}\right) \\ -gh(S_{oy}-S_{fy})+\frac{q_y}{h}\left(\frac{I}{2}\right) \end{bmatrix} \tag{2}$$

Where q_x = unit discharge in the x-direction (m^2/s), q_y = unit discharge in y-direction (m^2/s), h = flow depth (m), g = acceleration due to gravity (m/s^2) and n = Manning's roughness coefficient; $S_{f_x}=g\,n^2\frac{q_x\left(q_x^2+q_y^2\right)^{1/2}}{h^{10/3}}$; $S_{f_y}=g\,n^2\frac{q_y\left(q_x^2+q_y^2\right)^{1/2}}{h^{10/3}}$; I = infiltration rate and can be computed from Kostiakov-Lewis equation *(Playan et al. 1994)*.

$$I=ab\tau^{b-1}+c \tag{3}$$

Where τ = opportunity time (min), b = exponent and c = a coefficient (m/min). The time-integrated form of Eq. 3 provides the expression for the infiltrated depth,

$$z = a\tau^{b} + c\tau \tag{4}$$

COMPUTATIONAL METHOD

Fig. 1 shows the finite-difference discretization of the domain in two dimensions. Using McCormack finite difference approximation, Eq. 1 can be written as,

Predictor Step

$$U_{i,j}^{k*} = U_{i,j}^{k} - \frac{\Delta t}{\Delta x}\left(E_{i+1,j}^{k} - E_{i,j}^{k}\right) - \frac{\Delta t}{\Delta y}\left(F_{i,j+1}^{k} - F_{i,j}^{k}\right) - \Delta t\left(S_{i,j}^{k}\right) \tag{5}$$

Corrector step

$$U_{i,j}^{k**} = U_{i,j}^{k*} - \frac{\Delta t}{\Delta x}\left(E_{x_{i,j}}^{k*} - E_{x_{i-1,j}}^{k*}\right) - \frac{\Delta t}{\Delta y}\left(F_{y_{i,j}}^{k*} - F_{y_{i,j-1}}^{k*}\right) - \Delta t\left(S_{i,j}^{k}\right) \tag{6}$$

The value of the variable at the new time level is,

$$U_{i,j}^{k+1} = 0.5\,(U_{i,j}^{k} + U_{i,j}^{k**}) \tag{7}$$

The details of this procedure for solving the hydrodynamic equations are available in standard text in open channels *(Chaudhry 1993)*.

INITIAL CONDITION

Zero depth and discharge should be taken as initial condition. However, to avoid undefined terms resulting due to mathematical singularity at the beginning of the computation, a small positive value of 10^{-10} m is initially assigned to the depth of flow at all computational nodes in the domain. The same value is used to initialize q_x and q_y.

BOUNDARY CONDITIONS

The simulation of basin irrigation system requires the implementation of proper inflow boundary conditions. The numerical method used is applicable at all interior nodes only and special treatment is required for evaluating 'q_x', 'q_y' and 'h' at the boundary nodes. Three types of inflow boundary conditions are implemented in the model. These correspond to three irrigation practices namely line inflow, corner inflow and fan inflow. A description of each type is given by *Playan et al. (1994)*. For the line inflow the boundaries involved are the flow boundaries and the symmetry boundaries. A flow boundary can be either an inflow boundary or an outflow boundary. Pseudo boundary nodes are adopted to determine the boundary conditions especially if an explicit scheme is used *(Dholakia 1998)*. A reflection procedure is used at a symmetry boundary *(Roache 1972)*.

ADVANCE PHASE, RECESSION PHASE AND INFILTRATION

A procedure adopted by *Playan et al. 1994* is used to define the advance phenomenon by ignoring all flow depths smaller than a certain user-defined threshold (the minimum flow depth needed for the node to be considered as part of advancing front and that which allows infiltration to start). This minimum depth must be greater than the initial depth. Values equal to/or smaller than 10^{-3} m did not modify the advance rate of quasi-one-dimensional simulations *(Playan et al. 1994)*. The end of advance phase occurs when flow depth at all nodes in the domain is greater than the minimum threshold infiltration depth (10^{-3} m). The value of the time at this point is the time of advance. Similarly, the recession phase, thereby end of simulation occurs when the flow depth at all nodes in the domain is less than minimum threshold value.

STABILITY

Explicit finite difference schemes are stable as long as the *Courant-Friedrichs-Lewy (CFL)* condition is satisfied. For two-dimensional flows it is expressed as,

$$C_{2d} = \left(\frac{|V| + \sqrt{gh}}{\Delta x \Delta y} \right) \Delta t \sqrt{\Delta x^2 + \Delta y^2} \leq 1 \qquad (8)$$

Where, 'V' is the resultant velocity at the grid point. Eq. 8 has to be satisfied at every grid point at all times

VALIDATION AND COMPARISON OF MODELS

The computational model is developed to simulate the flow in level as well as graded basins. A comparison of this model with B2D and SIRMOD *(Playan et al. 1994)* is presented.

Line inflow

A narrow rectangular level basin is used to test the model in quasi-one-dimensional conditions *(Playan et al. 1994)*. The basin was 465 m long and 100-m wide, with an area of 46,500-m^2 and was irrigated from one of its 100-m sides. Water flowing in this field experiment was largely one-dimensional. The field had no significant slope. The infiltration parameters obtained were, a = 0.00893 m/min^b, b = 0.406 and c = 0.00000 m/min. A value of 0.1 was estimated for the Manning's 'n'. The field was irrigated with a constant discharge of 0.183 m^3/sec, measured with a broad-crested weir. The inflow was cut-off after 660 min. A quasi-one-dimensional simulation is performed using hydrodynamic model. A line inflow is defined along one of the 100-m sides of the basin and the grid spacing was set to 5-m.

Fig. 3 presents the advance profiles at times 180, 360 and 540 minutes simulated by SIRMOD, B2D and proposed hydrodynamic model BASIIT. Table 1 presents the advance and recession times for the field data as obtained by SIRMOD, B2D and BASIIT. Both SIRMOD and B2D underestimated the time of advance. B2D underestimated the advance by 5.5 % and SIRMOD underestimated by 3.6 %. Whereas, BASIIT underestimated the advance by 4.0 %. All the models produced a straight horizontal recession line because the field slopes were set to zero. B2D overestimated the average recession time by 0.4 %, while SIRMOD underestimated by 4.4 %. BASIIT overestimated estimated the recession time by 0.8 %.

Corner inflow

To test the two-dimensional predictive capability of the model, 216.1-m long by 183.2-m wide field having an area of 39,590-m^2 is used (*Playan et. al. 1994*). The infiltration parameters were determined by means of three dual ring cylinder infiltrometer tests as, a = 0.0168 m/min^b; b = 0.397 and c = 0.0 m/min. A value of 0.10 was estimated for the Manning roughness coefficient 'n'. The field was irrigated from its northwest corner with a constant discharge of 0.270 m^3/sec. The inflow was cut-off after 540 minutes. Field observed response is compared with results obtained by SIRMOD, B2D, and BASSIT model. A 21 by 21 grid is used in the models to represent the domain and the field is simulated as a corner inflow.

Figs. 4, 5, 6, 7 present the front configuration for corner inflow at 3h, 5h, 6h and 7h simulated by finite difference models BASIIT. The results obtained by B2D and SIRMOD are also presented in these figures. Table 1 also presents the advance and recession times as obtained by SIRMOD, B2D, and BASIIT. Both SIRMOD and B2D underestimated the time of advance. B2D underestimated the advance by 7.9 % and SIRMOD underestimated by 17.5 %. Whereas, BASIIT underestimated the advance by 8.0 %. B2D underestimated the average recession time by 0.4 %, while SIRMOD it underestimated by 15.4 %. Whereas, BASIIT underestimated the recession time by 0.78 %.

Fronts simulated by all the models are symmetrical for the second and third hour, while the corresponding fronts for field data show faster advance in the southern direction (Figs. 4-7). This seems to be due to the configuration of the inlet, microtopography and spatially varied infiltration. After the third hourly profile, the advancing front reaches the domain's southwest corner and the front configuration loses symmetry, but the effect of preferential flow towards the south is still noticeable in the field data. SIRMOD can only predict the front configuration as a straight line, while B2D and BASIIT approximate the front configurations.

The simulated advance by BASIIT compare excellently with the observed advance of level basins. Similarly, the simulated recession of the model compare satisfactorily. The results suggest that the explicit model can simulate the complete irrigation event with a fair degree of precision.

MODEL APPLICATION

High spots

A hypothetical case study is used to illustrate the additional feature of the model namely its capability to include high spots (Islands) inside the domain. A domain is sketched over rectangular grid composed of 21 rows and 29 columns, with a uniform grid spacing of 5m. An internal high spot is considered within the domain. A line inflow is distributed along north side of the domain, with a discharge of 0.250 m^3/s and a cut time of 50.0 min. The infiltration parameters are, a = 0.00346 m/min^b, b = 0.388 and c = 0.000057 m/min (*Playan et al. 1994*). Fig. 8 presents the overland water surfaces for times 30 minutes. The flow circumvents the high spot and both the flow branches meet on the downstream side.

A second hypothetical case study is considered to illustrate the flow past the high spot using corner inflow configuration. A corner inflow is distributed along a square field 100 m long, with a discharge of 0.1 m^3/sec. The inflow is cut-off after 60 min. Manning's 'n' is 0.04, and the infiltration parameters are a = 0.00323 m/min^b, b = 0.474 and c = 0.000098 m/min (*Playan et al. 1994*). Fig. 9 presents the overland water surfaces for time 40 minutes. In this case also the flow circumvents the high spot and both the flow branches meet on the downstream side.

Fan inflow

BASIIT is used to simulate the flow in a hypothetical square field 50 m long, with an area of 2500 sq. m., irrigated with a constant discharge of 0.05 m^3/sec using a fan inflow configuration. The inflow is cut-off after 30 min. Manning's 'n' is 0.04 and the infiltration parameters are, a = 0.00323 m/min^b, b = 0.474 and c = 0.000098 m/min. Different node configurations are used to represent field, ranging from 121 to 676 nodes domain. Table 2 presents the results of this test for the fan inflow. In this inflow configuration, Δt decreases as the grid becomes finer due to the effect of Δx and Δy. Flow depth and velocity are locally increased resulting in shorter time steps. Between 121 node and 676-node configuration, the variation in advance time is 12 % and in recession time is 1.6 %. The mass balance errors varied from 0.456 % to 0.683 %. Fig. 10 presents the overland profiles during the advance at 15 minutes.

Spatially varied infiltration

It is a common practice to conduct tests at several locations within each field to account for the effects of spatial variability. The parameters are then estimated statistically fitting a curve to the data pairs resulting from all the tests. The result is an averaged infiltration curve that represents the whole field.

The infiltration rate at any point 'p' in the field with an opportunity time 'τ_p' can be interpolated using an inverse distance square procedure *(Playan et al. 1994)*,

$$i_p = \frac{\sum_{j=1}^{m} \frac{b_j a_j \tau^{b_j - 1} + c_j}{d_{pj}^2}}{\sum_{j=1}^{m} \frac{1}{d_{pj}^2}} \qquad (9)$$

Where m = number of test sites, a_j, b_j and c_j = infiltration parameters corresponding to test site j; and d_{pj} = distance between the point p and the test site j (m).

BASIIT interpolates the value of the infiltration rate for each node in the finite-differencing grid and uses it to solve the governing equations for the dependent variables. The infiltrated depth at each node is then computed using the following expression,

$$z_p^{t+\Delta t} = z_p^t + i_p^{t+\Delta t}\Delta t \qquad (10)$$

The model is applied to a hypothetical square field with an area of 10,000-m^2. The inflow discharge is 0.100 m^3/s with an application time of 100 min. Only corner inflow cases were considered in this study. Five case studies are considered in the analysis of the problem. Case studies NWC, NEC, SWC and SEC correspond to water sources located in the Northwest, Northeast, Southeast, and Southwest corners, respectively. All of them implement spatially varied infiltration. Finally, the UNI case study corresponds to a uniform infiltration analysis of the problem, where the field is irrigated from the Northeast corner (Fig. 11) and infiltration is characterised by a statistical regression of the five test sites, which gives average values of, a = 0.00264 m/min^b, b = 0.639 and c = 0.000025 m/min.

Simulation results for all five cases are presented in Table 3. It compares the time of advance (T_a), time of recession (T_r), required depth (z_r), application efficiency (E_a), water requirement efficiency (E_r) and distribution uniformity of low quarter (D_u) for the different cases. Figs. 12 and 13 presents three-dimensional maps of infiltrated depth for case NEC and SWC.

In this hypothetical case study spatial variability of infiltration produces differences of about 22.8 % in application efficiency and 22.60 % in distribution uniformity of the low quarter for the different inflow locations. The performance of the case study with uniform infiltration (UNI) was better than the best case with spatially varied infiltration.

Indian Basins

In the first field experiment (WALBAS-1) a narrow basin is used to test the model in quasi-one-dimensional conditions. The basin was 75.0 m long by 10 m wide, with an area of 750 sq. m. Water flowing in this field experiment was largely one-dimensional. Two dual ring infiltrometers were used to estimate the infiltration parameters. The resulting infiltration parameters were a = 0.00923 m/min^b, b = 0.386 and c = 0.000078 m/min. A value of 0.1 was estimated for Manning's 'n'. The field was irrigated with a constant discharge of 0.147 m^3/sec from one of sides. The inflow was cut-off after 65 min. The field test procedure consisted of observations of the advance and recession times at every 5 m along both of the sides of basin by the authors.

In order to test the two-dimensional predictive capability of the model, the authors conducted the second field experiment (WALBAS-2). The experiment was performed in a basin 39.0 m long by 30.0 m wide with an area of 1170 sq. m. The infiltration parameters were computed as a = 0.00438 m/min^b, b = 0.412 and c = 0.000087 m/min. A value of 0.04 was estimated for the Manning's 'n'. The field was irrigated from a corner with a constant discharge of 0.019 m^3/sec and the inflow was cut-off after 35.0 min. Details of these experiments are presented elsewhere *(Dholakia 1998)*.

BASIIT is used for simulating the flow in study basins. Fig. 14 presents the comparison of observed and simulated advance and recession trajectories for basin WALBAS-1. Fig. 15 presents the field and simulated front configurations at 5 min, 10 min, 15 min, 20 min, 25 min and 30 min for basin WALBAS-2. The simulated results match closely with the field observed values.

CLOSURE

The paper presents a computational model for simulation of basin irrigation events. The boundary conditions and stability criteria are also discussed. The results of the models are verified using the observed advance and recession times for basin irrigation events. A good agreement of the results is observed. The model also demonstrates additional features like, considering fan inflow as one of the inflow boundary conditions, spatial variability in infiltration, simulation of high spots and its application to the Indian basins.

Table 1: Comparison of Characteristic times for data of Playan et al.(1994)

EXPERIMENT	TIME OF ADVANCE		TIME OF RECESSION	
	MINUTES	ERROR (%)	MINUTES	ERROR (%)
Field Experiment I				
FIELD DATA	670	-	1815	-
B2D	633	5.50	1822	0.40
SIRMOD	646	3.60	1736	4.40
BASIIT	643	4.00	1830	0.80
Field Experiment II				
FIELD DATA	570	-	1020	-
B2D	525	7.90	900	11.80
SIRMOD	470	17.50	863	15.40
BASIIT	523	8.0	1012	0.78

Table 2 : Results of numerical test for fan inflow

	FAN : TWO - DIMENSIONAL				
ROWS & COLUMNS	NODES	CPU TIME (MIN)	ADVANCE TIME (T_L) (MIN)	RECESSION TIME (T_R) (MIN)	MASS BALANCE ERROR (%)
11 X 11	121	0.153	19.37	123.159	0.683
16 X 16	256	0.710	20.21	124.200	0.592
21 X 21	441	1.940	21.19	124.700	0.562
26 X 26	676	3.940	22.01	125.100	0.456

Table 3 : Simulation results for cases SWC, SEC, NWC, NEC, UNI

CASE	T_l Min	T_r Min	z_r m	E_a %	E_r %	D_u %
SWC	106.540	178.600	0.0414	69.10	97.52	70.75
SEC	107.542	177.500	0.0326	53.30	97.28	54.79
NWC	102.292	180.200	0.0403	67.17	98.60	68.12
NEC	112.347	174.600	0.0333	55.50	98.97	56.08
UNI	097.329	159.400	0.0420	70.00	99.07	70.66

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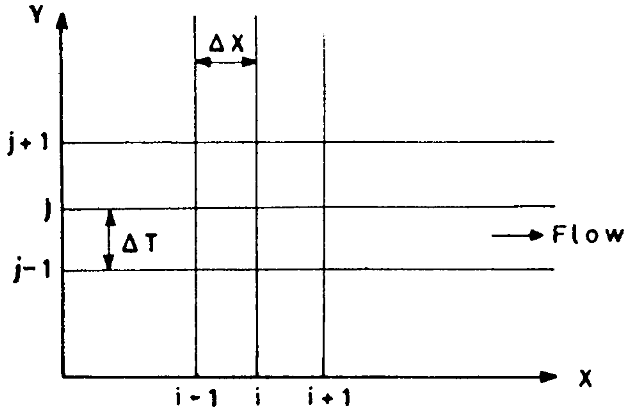

Fig. 1 : Finite Difference Discretisation of the Domain

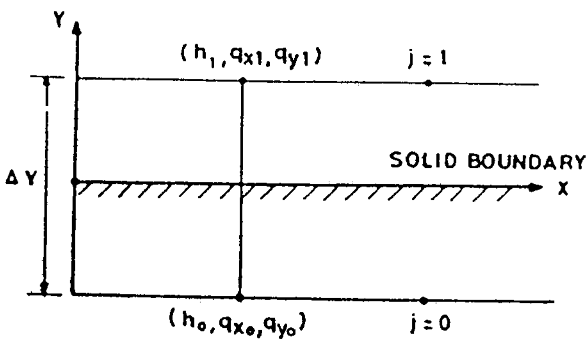

Fig. 2 : Reflection Boundary

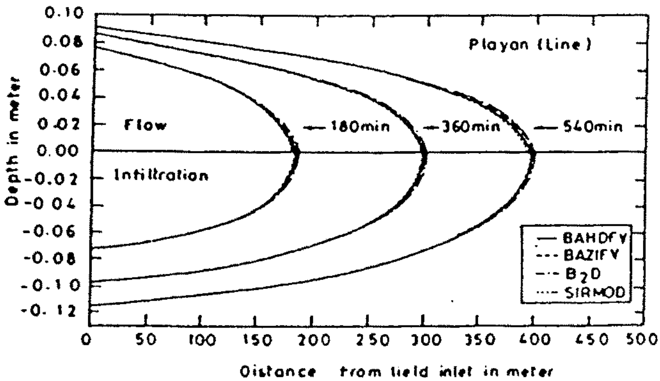

Fig. 3 : Overland and infiltration profiles (Line Inflow)

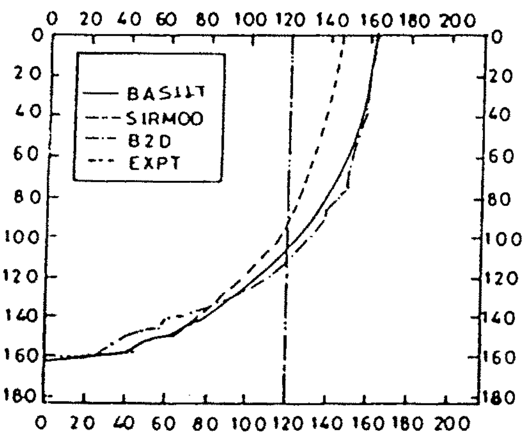

Fig. 4 : Front Configuration at 3 Hour for Level Basin (Corner Inflow)

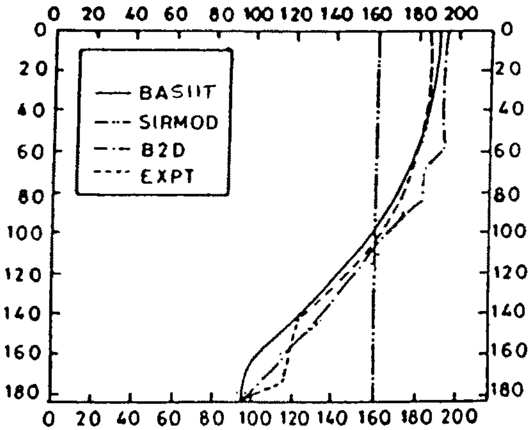

Fig. 5 : Front Configuration at 5 Hour for Level Basin (Corner Inflow)

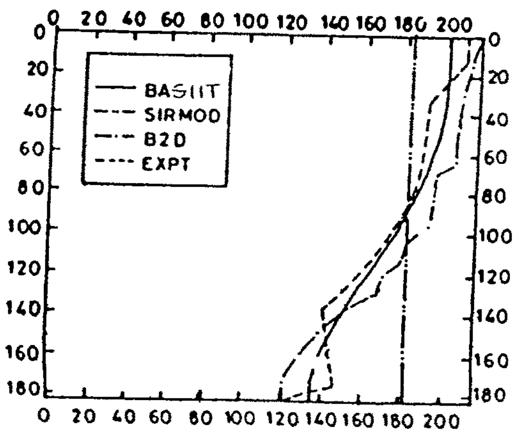

Fig. 6 : Front Configuration at 6 Hour for Level Basin (Corner Inflow)

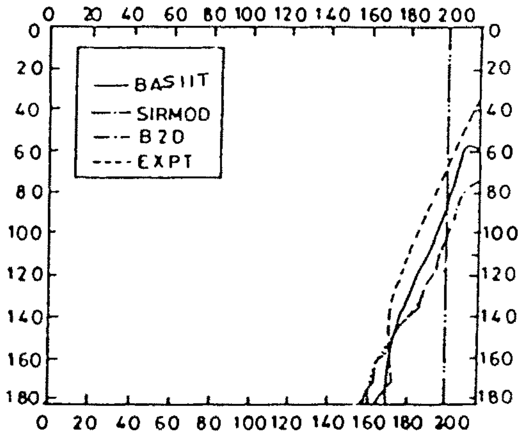

Fig. 7 : Front Configuration at 7 Hour for Level Basin (Corner Inflow)

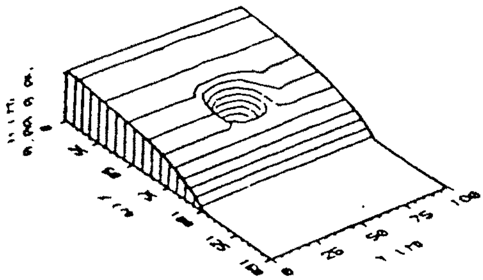

Fig. 8 : Flow Past High Spot at 30 Min (Line Inflow)

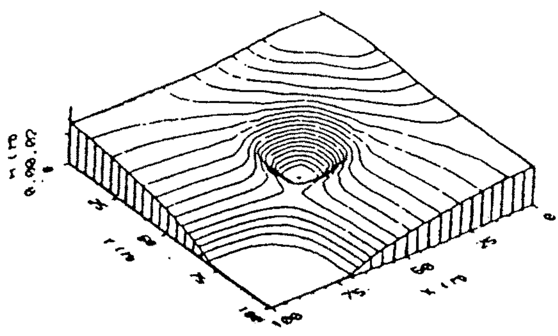

Fig. 9 : Flow Past High Spot at 40 Min (Corner Inflow)

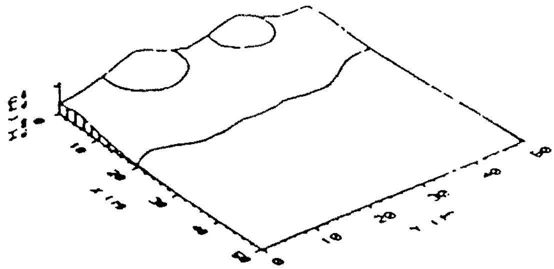

Fig. 10 : Overland Profile at 15 Min (Fan Inflow)

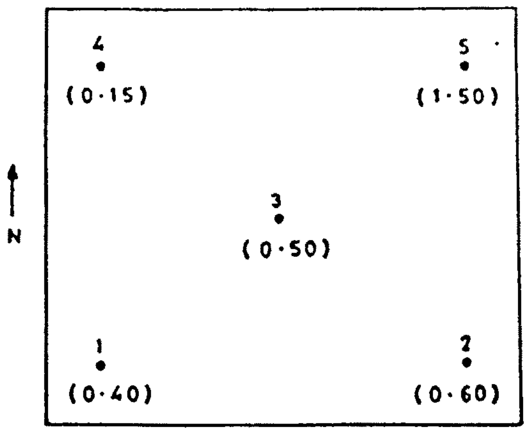

Fig. 11 : Location of Infiltration test sites

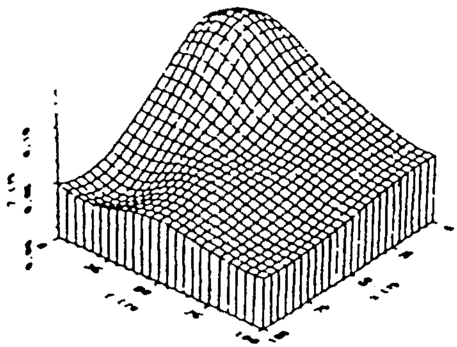

Fig. 12 : 3D map of Infiltration Depths for NEC

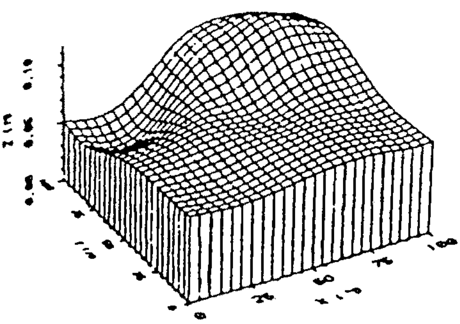

Fig. 13 : 3D map of Infiltration Depths for SWC

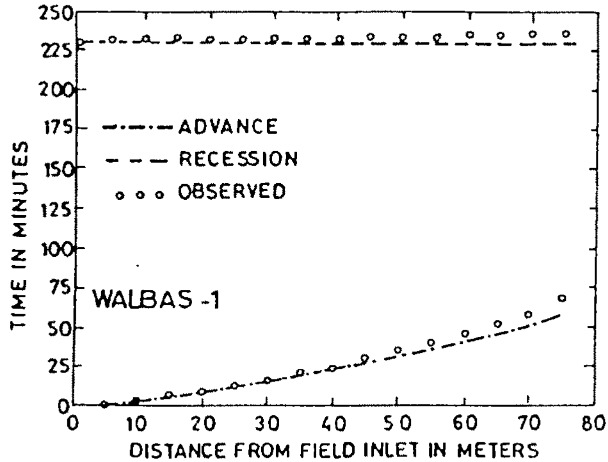

Fig. 14 : Observed and Simulated Advance and Recession Trajectories (WALBAS-1)

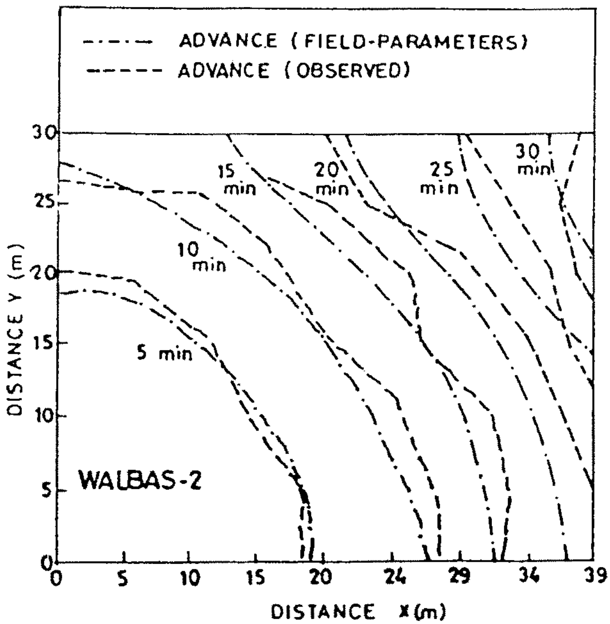

Fig. 15 : Observed and Simulated Advance and Recession Trajectories (WALBAS-2)

ORGANIZATIONAL ENGINES OF WATER PRODUCTIVITY, SOCIAL JUSTICE, AND ENVIRONMENTAL SUSTAINABILITY IN THE POUDRE RIVER BASIN OF NORTHEASTERN COLORADO

David M. Freeman[1] John Wilkins-Wells[1]

ABSTRACT

Non-profit cooperative associations of irrigators--known as Mutual Companies–divert, transport, and manage irrigation water across the arid landscapes of the Western United States. These local organizations empower people to provide themselves with agricultural water under control. This paper describes general attributes of mutual companies and reports that 18 mutual companies operating canals and reservoirs in the Poudre River Valley of Northern Colorado have evolved organized patterns of water use, exchange, and re-use that contribute importantly to water resource productivity, distributional justice, and environmental sustainability. Daily water re-use ratios average 1.9:1 over a 24 year period (1970-1994) and sometimes rise as high as 3.3:1 in a calendar year. This level of water re-use is made possible by the 18 mutual companies and the arrangements that they have made among themselves and other water users over the last century. By studying the attributes and capabilities of mutual companies, we can distill lessons regarding how human beings can better organize themselves to manage water.

OBJECTIVE

It is the objective to examine a set of organizations diverting and managing irrigation water in the Poudre River Valley of Northern Colorado. They are non-profit cooperatives known as Mutual Companies. Mutuals are incorporated or unincorporated associations of irrigators who have organized themselves for the collective task of diverting, transporting, and managing irrigation water in their canal command areas. This form of local organization is strategic to any policy attempts to improve water resources management in the arid Western United States because they are central to:

1. enhancement of water productivity that is critical to agriculture, municipalities, and industry;

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2. improvement of distributional justice among multiple and conflicting water users;

3. advancement of environmental sustainability via improvement of wildlife habitats.

By studying the attributes and capabilities of mutual companies, we can distill lessons regarding how human beings can better organize their water resources. There is much at stake in the investigation of a form of organization that empowers people to transcend individualistic self-seeking behaviors in marketplaces and that provides socio-political space for communities of resource appropriators to 1) democratically conduct discourse about resource policy; and 2) to adapt themselves and general national policies to local site-specific conditions.

MUTUAL IRRIGATION COMPANIES

Mutual Companies, non-profit cooperative associations of irrigators, have been constituted to divert, regulate, store, and distribute water to members primarily for irrigation of agricultural crops (Maass and Anderson, 1978; Dunbar, 1983: 29-35). With urbanization and industrialization of their canal command areas, they also increasingly integrate into their operations municipal, industrial, and environmental agendas (Wilkins-Wells, 1999). Mutual Companies constitute by far the greatest proportion of irrigation organizations in the Western United States and they serve about 45% of the irrigated acreage (Table 1). Obviously, Mutual irrigation associations are a most strategic form of local organization on the Western water scene.

As European settlers established irrigated agriculture in the arid regions of the Western United States in the late 19th and early 20th centuries, they everywhere faced the problem that construction of river diversion works, ditch systems, and reservoirs required large outlays of economic capital–sums far exceeding their capabilities individually or in small groups. The general response was for farmers to mobilize themselves into mutual ditch associations for the purpose of combining resources to undertake the work collectively as a community of irrigators.

As an organizational form, mutual irrigation associations share some common attributes:

1. Farmers and their associations do not own water; water is publically "owned" by all of the people of the respective states. Mutual ditch associations have secured a right under state appropriation doctrine to divert water for beneficial use and they mobilize the revenue from their membership of water

Table 1. Types of Organizations As Percentage of Western State Total, 1969

Irrigation Organization	Percentage of All Organizations	Percentage of All Acreage Irrigated By Organizational Type
Mutual Water User Cooperatives	86.3	45.1
All Districts (Irrigation & Other)	9.1	47.1
Bureau of Reclamation Constructed and Operated	.7	1.8
Bureau of Indian Affairs	.7	2.9
State and Local Governments	.5	.2
Commercial Companies	2.7	2.9
	100.0	100.0

Source: U.S. Bureau of the Census, Census of Agriculture, 1969. Vol. IV. Irrigation. U.S. Government Printing Office, 1973 p. xxv. This represents the most recent data available given that such organizational data have not been reported in subsequent census efforts. There is, however, good reason to believe that these data closely reflect present realities.

users to pay annual costs of managing the resource while it flows through their canal command areas. In addition, revenue is raised to pay non-routine costs of initial capitalization of canal and other works, and periodic rehabilitation.

2. An organizational centerpiece is a system of water shares. Farmer-members transferred any individually held water rights to their mutual ditch company and, in return, received shares of stock representing their fraction of investment in the collective enterprise. These shares of the association's collective water and physical assets could then be bought, sold, or leased among shareholders within the canal network. The concept of water share (Freeman, 1989: 27-29) is two-sided: 1) on one hand it confers a benefit–organized delivery of a fraction of the Mutual's water under appropriate control to meet crop or other demands; and 2) it imposes an assessment obligation upon each shareholder to pay a proportionate "fair share" of organizational management cost. Example: costs of water management are summed for an operating year and if irrigator X received 5/100's of the beneficial water flow, X would be assessed 5/100's of the organization's cost of managing and delivering that flow.

3. The organizations are non-profit. Revenues are mobilized to the extent necessary to cover costs and no more than necessary to provide for emergency contingencies. It is in the interest of members to assess themselves as little per

share as possible to keep costs as low as possible for the water resource. Incorporated Mutual Companies, registered with the Secretary of State, must submit annual reports to establish that their operations are conducted within the legal parameters established by the enabling legislation for such non-profit enterprises.

4. Shareholders democratically establish policy and elect Boards of Directors (typically 5-7 leaders from the irrigation community) to implement policy adopted by shareholders at annual meetings and to oversee daily management. Boards, in turn, employ the necessary staff for operations and maintenance. Association policy, including establishing annual share assessments, is established by voting shares of organizational stock. Unlike stock in private corporations that delivers a periodic dividend check, stock in mutual companies delivers no monetary benefit but does provide a benefit in the form of water deliveries under community control.

Mutual Companies in Colorado's Poudre River Valley

The Cache La Poudre river drains a modest area (about 1,900 square miles) and appears as little more than a short wisp of line on the typical highway map used by travelers contemplating North Central Colorado. The river, in its physical and biotic aspects has been described (Evans and Evans, 1991) and a scholarly summary of the operation of irrigation organizations in the Poudre river valley is also available (Anderson, 1978). The main stem flows about 80 miles from its source in Rocky Mountain National Park (Poudre Lake placed just below the Continental Divide at nearly 11,000 feet of elevation) to its mouth east of Greeley, Colorado at about 4,600 ft. where it becomes a major tributary to the South Platte.

Europeans came to the Poudre valley first as trappers linking Native Americans to the global fur trade, then as gold seekers (especially the 1859'ers), and then following the Civil War as settlers lured by the Homestead Act. Scarcity of water supply on the East Slope of the Rocky Mountain front has constituted a major constraint for all peoples. Native Americans adapted their summer and winter hunting and foraging patterns to the realities of small surface streams etching highly variable and frequently dry pathways across a vast landscape. Miners had to divert small "heads" of water across considerable distances via sluices to work ore fields located above stream bottoms. Agriculturalists, either as disappointed miners or as fresh homesteaders, sought opportunities to provide themselves subsistence and cash by diverting water out of the Poudre river bottom to irrigate crops in a region where annual rainfall averaged 14 inches.

Demand for agricultural and municipal water soon exceeded supply. Most irrigation canals were constructed between 1860 and 1881 by which time the river was substantially over-appropriated. Water flows in the Poudre valley in a reasonably predictable pattern–highest snowmelt flows pass through in mid-June (well before peak crop demand) and quickly diminish by early July (Figure 1). To serve an 1881 right under the operative distribution rule of "first in time, first in right," all prior ditch headgate rights would have to be filled and that would require a river running at 3642 cubic feet per second.

A glance at Figure 1, the river hydrograph, reveals that a) there is much variation of river flows from season to season; and b) such a substantial flow does not exist, on average, at any time in the irrigation season without even considering the fact that the river can be counted upon to rapidly diminish after peak flood flows. Soon, therefore, mutual companies–especially those with more junior river rights-

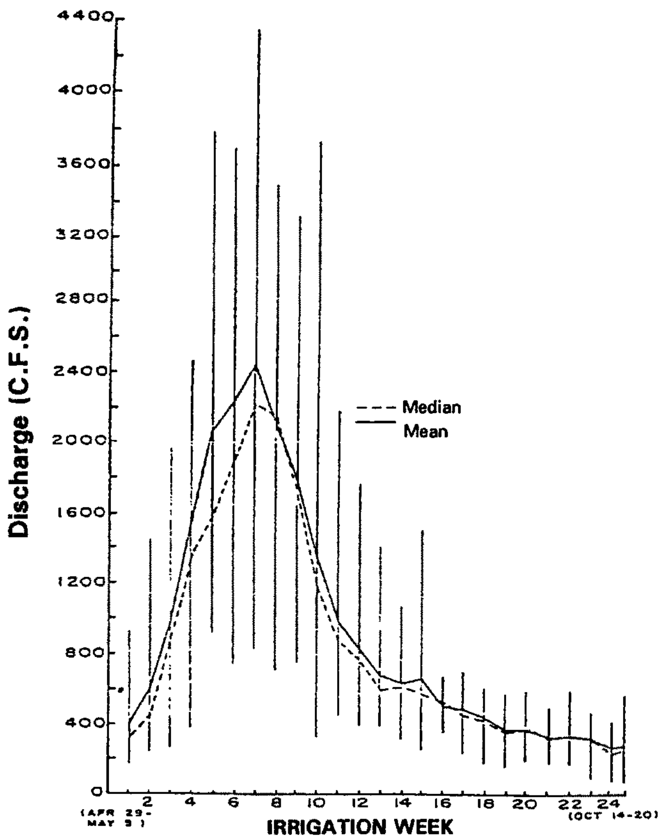

Figure 1. Poudre River Hydrograph

-set about to supplement river flows with reservoir storage as opportunity permitted. Water was thereby diverted off-season--and during those brief periods during the cropping season when flows exceeded demand--into reservoirs for use when required, especially mid-to-late summer to sustain crops.

The essential reality of the Poudre river basin, as has been the case throughout much of the arid west, is that there has never been a time of water surfeit. Water has always been the limiting factor constraining the quest for production, distributional justice, and habitat for other living things.

In the over-all Poudre and downstream South Platte system, over 100 irrigation organizations serve more than 500,000 acres of irrigated land (Anderson, 1978: 284). Almost all these organizations are mutual companies--a few are Irrigation or Conservancy Districts. The irrigation canals of the Poudre valley are owned and operated by 18 Mutual Companies, all of which were established in the late 19th century and, possibly after having gone through one or more reorganizations, continue to operate in the 1990's. Some possess both reservoirs and canals, some possess only service canals, and some operate only as reservoir associations.

Mutual Companies Created A Spaceship Recycling Economy

Three decades ago Kenneth Boulding (1968) developed a pair of metaphors distinguishing a "cowboy" economy from that of a "spaceship." People in "cowboy" economies exploited resources without regard for sustainability, paid little heed to negative spillovers of their activities, and generally assumed little or no interdependence among users or with the natural world. Resources were looted to the limit and then abandoned leaving a trail of degraded environments and broken communities. On the other hand, a spaceship economy was taken to mean an organizational system whereby people managed their resources for sustainability, where attention was paid to intimate interdependencies among people and their natural environments, where negative externalities were internalized by decision-makers who produced them, where there was priority for recycling scarce resources for long term life support.

In the context of the unrestrained frenzy of globalized economic growth in the late 20th century, we may be prone to think of spaceship economies, and the social capital that it takes to produce them, as being in the distant future--if possible at all. However, a close look at the 18 mutual canal companies of the Poudre river valley, and an examination of how scarce water is organized on that landscape, provides insight into the workings of a spaceship water economy that has been functioning for decades. Here water has been organized in ways that have enhanced water productivity, distributional social justice, and has done so in a manner that makes room for incorporation of new environmental agendas centering on upgrading open spaces and riparian wildlife habitat.

Organizing Water at the Canal Level

After water has passed through the canal headgate at the river, the Poudre valley mutual companies distribute water employing variations on a common principle--i.e. water is delivered in amounts proportional to shares owned in the organization (Anderson, 1978). A key aspect of water delivery is that water is volumetrically measured to fulfill each user's quota per share owned on the common ditch. Shareholders receive their proportional share without respect to their location in the ditch command. This has three consequences:

1. Water productivity is much enhanced because water is as much available in the tail reaches of a given ditch as in the areas toward the head. Water productivity is fundamentally a function of water control; water must arrive at the time, and in the amount, required by crop consumptive needs. Unlike many systems elsewhere (Freeman, *et. al.*, 1989) not served by the Mutual Company form of social organization, there is no necessary decline in agricultural production in the middle and tail reaches of the canal due to mal-distribution of water. Water may be delivered on demand (if there is sufficient reservoir storage available) or upon some form of rotation but water will be available in a timely manner at all points along the canal to fill crop consumption and soil leaching requirements.

2. Distributional justice among users is made possible by the fact the losses in earthen ditches are shared by the entire canal community. Water losses in an earthen ditch are a function of channel length and condition. Those irrigators nearer the tail will, in general, be disadvantaged in receiving their water if one simply takes water from the canal during a given time period–e.g. the amount that would run during one hour or one day. Obviously, in the absence of an organization to prevent it, less water will flow in tail reaches per time period than at the head because of leaks, seepage, and evaporation–not to mention the depredations of users taking more than "fair share" amounts above one's field gate. However, if the organization distributes water by volume per share, and if volumes are measured so that losses anywhere on the common channel reduce volumes to all irrigators, then all farmers absorb the water loss and all have an incentive to reduce losses wherever they occur–the "shrink" has thereby been " socialized." For example, if irrigator X is served by a leaky length of ditch, and if a specified volume of water must be delivered to "X's field outlet, it will take a much longer time to deliver that specified volume to X than would be required if the ditch were improved. Farmers at all points in the canal command can see that water lost in delivery to X–to fulfill X's quota measured in acre feet per share--is water lost to themselves. All are advantaged by improving ditch performance without respect to their location. This fact strengthens canal communities of common interest and promotes distributional justice as well as water productivity.

3. Given that each share not only delivers benefit but also carries an assessment to pay a fraction of organizational management cost, ownership of excessive shares relative to crop demand imposes the burden of paying assessments on the unneeded shares. Therefore, there is an incentive for each irrigator to be innovative in reducing demand for water and thereby minimize the number of shares owned to keep assessments as low as possible. This fact, in turn, has two positive consequences: a) there is disincentive to purchase more shares than needed simply to dominate organizational voting; and b) there is constant quest to improve water use–and thereby reduce–total seasonal cost of irrigation water.

Organizing Among Canals – Exchange

The fundamental principle for river flow allocation among canal and reservoir headgates is "first in time, first in right." This notion is rooted in a fundamental ethical concern–i.e., those who came before and who have invested in the community irrigation works should be protected from the depredations of those who came after. In the late 19th century, prior to development of an adequate river regime, there was incessant threat that latecomers could open a headgate upstream, divert water away from longer established headgates, and thereby bring ruin to those who had already invested much to build their communities. The doctrine of "prior appropriation," properly organized and implemented, removed that threat and served the ethical concern that those who have invested in good faith should be protected.

Prior appropriation doctrine succeeded in creating zones of investment security within which stable life-plans could be socially constructed, but it left junior appropriators without sufficient water in most years. Water users in all supply situations tended to face significant scarcity, but junior appropriators, especially, had incentive to increase their supplies given that the river flows would generally not rise to a level necessary to serve their "calls" given that those senior to them had to be served first.

The solution was, for many water users, to construct reservoirs, and to store off-season (winter) flows on a separate winter season "first-in-time, first-in-right" priority system. However, this could only work if a storage reservoir could be located at a place on the landscape that would serve well the investing organization. All too often storage opportunities did not occur at places capable of serving, by gravity flow, the investing community. The solution was water exchange.

The basic idea of a water exchange is simple; it consists of a trade of water between two or more users from one point of diversion to another. Exchanges must be completed in such a manner as to prevent injury to the vested water rights of others. Depicting a typical situation, Figure 2 assists in explaining how exchanges work and why they are fundamental to creation of a spaceship water economy in the Poudre river valley. Organization A has a topographical opportunity to store water in a surface reservoir which can be filled by gravity by its supply canal (Figure 2). However, the reservoir is too low for Organization A

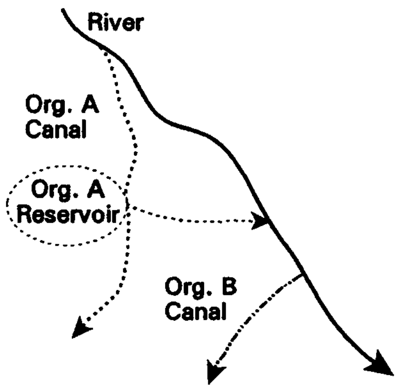

Figure 2. Water Exchange

to release that reservoir water back into its own canal. Rather than build pumps to physically lift A's storage water into A's supply ditch for its own shareholders–an expensive option given initial capitalization and recurring costs–Organization A releases water back to the river when requested by Organization B which has a downstream headgate capable to taking the water by gravity flow. B works with the river commissioner (who is responsible for administration of the prior appropriation doctrine) to allow Organization A to take B's water knowing that, at a mutually agreed time, Organization A will pay its water debt to B in equivalent volume. Both parties are better off. Organization A has expanded its supply of water available to its shareholders by developing a reservoir of water that it cannot use except as trading stock, by legitimately taking B's water at A's headgate, and by paying back the debt with water that it has stored. B, in turn, has gained flexibility and control that comes with having a water bank account in A's storage that releases B from the constraint imposed by fluctuating and declining summer river flows. Water has moved uphill from B to A and back to B by virtue of an exchange agreement implemented at minimum of transaction cost and at no cost in time, economic capital, or hydrocarbon energy. Social capital, in the form of mutual companies, has substituted for money and physical energy.

There are hundreds of such water exchanges conducted in the Poudre river valley of which eleven are major in the sense that they occur regularly and involve substantial amounts of water relative to the total annual flow of the river. Exchanges increase productivity when they improve timing of water deliveries relative to crop, municipal, and industrial demands. They increase distributional justice when they provide additional water to those with junior river rights. They enhance ecological sustainability when a Mutual Company permits water it normally would divert from the river bottom to flow past its headgate and through critical riparian habitat knowing that it will stored by another entity lower in the river and be exchanged for another company's water when needed. Exchanges are a major tool for constructing the spaceship water economy.

Organizing the Common Property Resource Among Canals – Water Re-Use

The mutual companies of the Poudre valley have created an approximation of the spaceship water economy not only by exchanging water across the landscape with positive consequences but also by developing capacities for multiple re-uses of this scarce commodity. Water users are not only highly interdependent within canal commands, and also among canals via systematic water exchanges, they are also interdependent because they generate return flows to other users (human and wildlife) down gradient from higher to lower canal, from canals to wells, from wells back to canals and to the river.

To assist in clarifying the point, Figure 3 provides a simplified schematic diagram of four major canals in the valley and their location relative to each other. Not represented on Figure 3, are 950 agricultural irrigation wells distributed from the command of the upper canal (North Poudre) to below the lowest ditch. The wells pump from an aquifer which is, itself, sustained by canal seepage and deep percolation. The over-all direction of water flow is from the northwest downslope to the southeast. Of that water which is diverted higher in the system, a goodly portion is not consumptively used by the first appropriator, and it then moves to become part of another source of supply where it is again diverted by canal or pump.

As water is delivered to any given party, a fraction is consumptively used (e.g., evapotranspiration through plants to the atmosphere, evaporation from a reservoir, wetland, or cooling tower) and a fraction leaves the user's system as runoff or discharge that creates a return flow to other down gradient users. Return flows are created by:

1. seepage from canals and reservoirs. The Poudre basin ditch and reservoir system efficiency is about 55%, meaning that water available at the average field is 55% of the water diverted at the average headgate and transported in the average canal.

2. deep percolation of water below the root zone of irrigated fields which

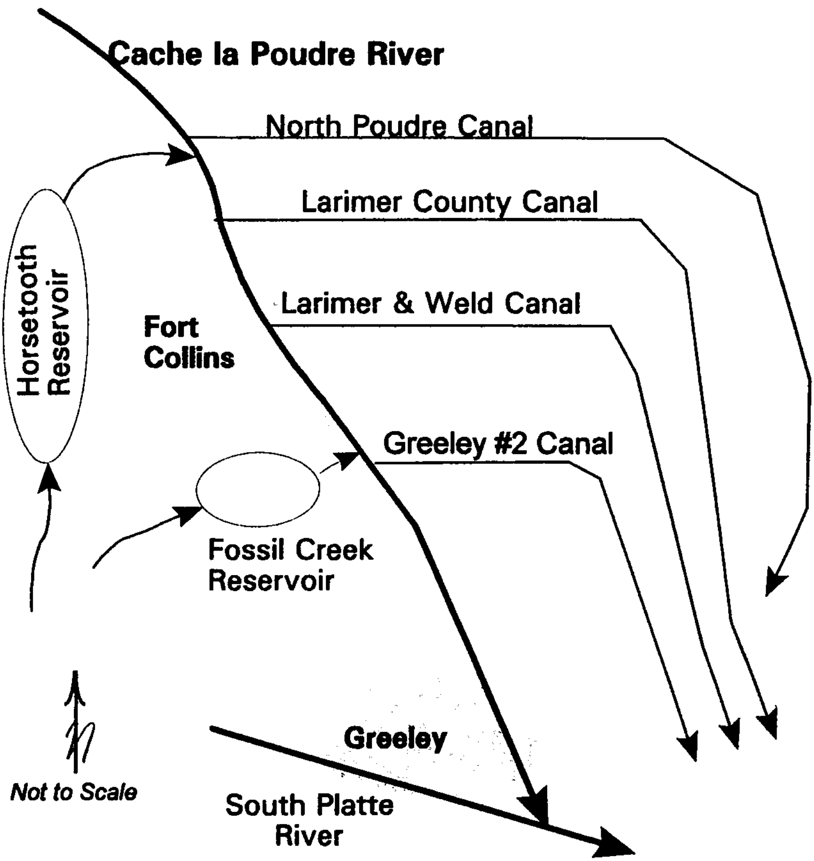

Figure 3. Schematic of Four Principal Poudre River Mutual Company Canals

then makes its way back downslope to other canals and the river.

3. surface run-off from irrigated fields.

4. municipal-industrial discharges back to rivers.

In such a system one user's "wasted" (i.e. non-consumptively used) return flow water is another user's supply. Inefficiencies in farm application of water can create high over-all system efficiencies as seen in the Poudre valley re-use ratios reported on Table 2. The waste of one appropriator is an asset to others and to other living things. A literature has developed around the notion that Western

Table 2. Poudre River Water Re-Use Ratios 1970-1994

Month	Monthly Ratios	Daily Ratios	Maximum Daily Ratios
November	1.99	2.35	4.20
December	1.76	1.94	3.72
January	1.65	1.71	2.69
February	1.60	1.68	2.40
March	1.49	1.69	3.26
April	1.78	2.17	3.95
May	1.22	2.43	3.00
June	1.20	1.55	1.92
July	1.33	1.39	2.09
August	1.51	1.60	2.62
September	1.92	2.52	5.00
October	1.69	2.14	4.65
Average Re-use Ratio	1.6	1.9	3.3

Re-use ratio: total measured water diverted below Poudre Canyon Mouth River Gauge/ total measured water in river at Canyon Mouth River Gauge plus Horsetooth supplement

water has been, and is, wasted in large volumes (Postel, 1992: Reisner, 1986; Gleick, 1998: 19-24) and that the demonstrated inefficiencies are to be lamented and prevented. There needs to be a more thoughtful debate on this point. The analysis here accepts the fact of inefficiencies in water delivery and application as measured at a given point in the system but then asks: where is the so-called "wasted water" going and with what effect on human beings and other living things? Insofar as it is going to other users–human and wildlife habitat–to serve beneficial uses that address problems of productivity, distributional justice, and environmental sustainability, there may be redemption in inefficiencies as measured at any particular segment of the over-all river-canal-reservoir network in the valley. Table 2 reports Poudre river water re-use ratios for the 24 year period 1970-1994. The ratio expresses the total quantity of water diverted by all users in the valley (numerator) as compared to the actual water available in the river (denominator). The ratio values report that substantially more water is diverted than there is water available in the river during a given month, day or year. For example, given a daily average reuse ratio of 1.9, if 150,000 acre feet of water was available at the top of the basin in a given year, actual user diversions of water molecules amounted to 285,000 acre feet. Such a ratio is possible only in a spaceship water society that, in turn, is made possible by the Mutual Company form of social organization operating on a landscape congenial to the project. Several notes are in order:

1. Re-use is highest during fall and winter months when there little or no agricultural crop demand. Agriculture is, by far, the biggest user of water and its consumptive uses are heavy in summer months during which time reuse ratios markedly decline.

2. On the highest reuse days, water in the basin is recycled as much as 4 or 5 times in a stretch of river less than 45 miles long.

3. Cities and industry, if they are good stewards of their water, do not typically impose consumptive uses as high as does agriculture. Therefore, as urbanization and industrialization encroach on agricultural uses, water is often released to new uses. The challenge will be to put such water releases to uses that enhance ecological sustainability, to preserve strategic agricultural land and the open spaces that come with it, to enhance distributional justice for farmers relative to the urbanite, and to avoid unthinking watering of suburban and rural sprawl.

IMPLICATIONS AND CONCLUSION

Mutual associations of water users empower people with the capacity to undertake collective action on agendas of common community concern. Mutuals make possible the collective effort necessary to run irrigation canal networks, they can collectively "share the shrink" among all members without respect to location in the canal command so as to create a common interest of all in the irrigation enterprise, they can conduct water exchanges and exploit water re-use opportunities that make for enhanced water productive, distributional justice, and environmental sustainability.

This paper has briefly summarized essential attributes of the Mutual Companies found in the Poudre River Valley of Northern Colorado. Mutual cooperative water associations have empowered water users to provide themselves with a critically important common property resource–water under control. This form of social organization has mobilized human capacity to create something approximating a "spaceship" socio-economic system of water exchange and re-use. Non-profit Mutual Companies substitute social organization for money and hydrocarbon energy, and they take advantage of opportunities to re-cycle scarce water resources among multiple and competing uses--agricultural, municipal, industrial, and wildlife habitat.

The common property resource described here cannot be produced by individual self-seeking rationality of marketplace exchange. There would be no ear of corn, bale of alfalfa, or bag of pinto beans for marketplace exchange if there was no higher level of organizational rationality operating the common property water resource that makes private enterprise possible and rewarding. People operate with an individualistic calculus in the world of private marketplace exchange. Those same people must also operate as social organizational agents and entrepreneurs who can transcend the limits of individual rationality and provide themselves with a common property resource that draws them into the civic life of a larger community. The water users of the Poudre valley have found ways to actively pursue both dimensions of life; it behooves us to contemplate how others can follow their lead with regard to organizing water for better productivity, distributional justice among senior and junior appropriators, and insuring water availability for environmental agendas.

Sociological analysis must make room on its working agenda to examine carefully the nature of the organizations that encompass, constrain, and guide individual rationality in markets. In doing so, sociologists may well find ways to better approach issues facing us in the domain of water resources. The study of Mutual Companies–and other forms of local water organization in the arid West–can be expected to lead to more adequate specification of the attributes of organizations successful in producing and sustaining organized collective action in water resources management.

Many, if not most, natural resource problems found on the landscapes of the planet are common property resource problems that require people to mobilize for collective action in a context of high interdependence and a need to control free-riding–e.g., water resources, social forestry, livestock grazing, fishing and fisheries management. For example, effective local organization to protect a forest in Nepal from the ravages of individual sub-optimizing rationality in exploitation of fuel wood would produce a range of valuable services–protecting soils, controlling erosion, reducing downstream siltation and flooding, recycling wastes, providing habitat for plant and animal species. Sustenance of such a forest is the best and cheapest way to insure the continued supply of essential services for sustainable local, national, and international development. The form of social organization managing irrigation ditches in the Poudre valley may–when invested with appropriate local cultural content–be capable of mobilizing local peoples in South Asia and elsewhere to allocate fuel wood and other resources according to viable distributional share system designed to insure sustained yields, to connect delivery of the forest benefits with fulfillment of organizational obligation to the forest, to prevent individual free-riding, and to establish terms and conditions under which globalized economic capital is permitted to penetrate into local resource areas. By examining the attributes organizations in Northern Colorado that have historically empowered people to do things collectively that could never be accomplished individually in marketplaces, we may glimpse a path to a more sustainably productive and distributionally just future.

Acknowledgments

We wish to express our thanks to Mr. Jon Altenhofen, Professional Engineer, Northern Colorado Water Conservancy District, who calculated the data appearing in Table 2, Poudre River Water Re-Use Ratios, 1970-1994. We further appreciate the able graphical and editorial assistance of Ms. Annie Epperson.

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REDUCING MASS FLUX OF DRAINAGE SALTS

Jeryl R. Gardner[1] J.C. Guitjens[2]

ABSTRACT

Irrigation of arid and semi-arid agricultural regions has produced salinization and waterlogging problems. Tile drainage systems will effectively lower the water table and transport salts out of the root zone. However, the salts exiting the irrigated soils via drains cause new problems, such as reducing groundwater quality and damaging wetlands habitat. This research investigates the simulation of management alternatives that control drainage and the mass flux of salts in the drainage water and demonstrates an improvement over the use of leaching fraction and leaching requirement as conceptual models.

HYDRUS_2D, a two-dimensional Windows-based modeling environment, is used to simulate solute transport under the influence of alternative irrigation management practices for an alfalfa crop. HYDRUS_2D uses a finite element technique that numerically solves the Richards equation for saturated/unsaturated flow, and the Fickian-based advection/dispersion equation for solute transport in variably saturated porous media. The response to management alternatives (depth of irrigations, using water sources of varying quality in irrigating a soil with varying salinity) allows managers to evaluate the influences on the mass flux of salts in drainage water before they put a new approach into practice. The results include graphical displays of water and solute fluxes and the salt distribution in the upper soil profile.

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INTRODUCTION

The 1902 Reclamation Act created many western water projects, one of which is the Newlands Project. The goal of the Newlands Project was to "reclaim" arid lands in west central Nevada for human use. Construction of the Lahontan Dam created the Lahontan Reservoir that stores flows from the Carson and Truckee Rivers. Once the canals were in place, farmers began irrigating formerly non-productive lands with the high-quality river water. Irrigation dramatically raised the water table, creating salinity and waterlogging problems. Evapoconcentration increases the salinity in the root zone. Water above and beyond the crop's water requirements leaches salts out of the root zone, but increases drainage volumes and solute mass fluxes (Postel, 1999). Drain effluent and canal seepage water discharge into the neighboring Stillwater Marsh and Carson Lake wetlands. The canal diversions have not only reduced the quantity of water reaching the wetlands, but also the quality of the wetlands waters (Chambers and Guitjens, 1992).

OBJECTIVES

The objective is to quantify and to demonstrate with HYDRUS_2D the solute flux and the salt distribution in the soil profile under various irrigation management strategies.

BACKGROUND

NARC Site

In 1977, a system of perforated tile drains was installed in an experimental field at the Newlands Agricultural Research Center (NARC), with the twin goals of reducing the height of the water table and removing leached salts. The NARC study site is located in Fallon, Nevada, in the Lahontan Valley (Fig.1). The Carson Desert is a mid-latitude desert with cold winters and hot summers. The area receives an average of about 13 cm of natural precipitation annually, far less than the amount needed for crop production.

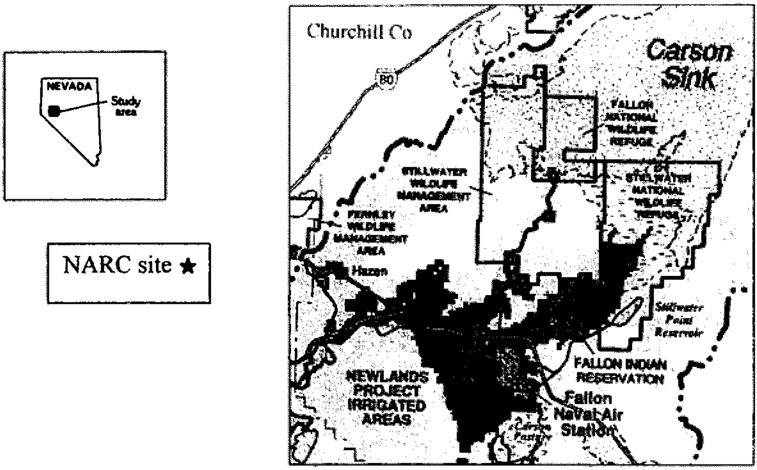

Fig.1. Location of Newlands Agricultural Research Center, Fallon, Nevada (Trionfante and Peltz, 1994)

The Carson Desert, a typical closed basin, is composed of mostly late Tertiary and Quaternary deposits, and lacustrine sedimentary deposits. These valley sediments were derived from the surrounding NE-trending fault-block mountains composed predominantly of olivine-basalts, rhyolites, hornblende and pyroxene andesites, mostly occurring as tuffs (Willden and Speed, 1974). They are easily weathered, contributing to the rapid salt dissolution. Glancy (1986) identified 4 principal aquifers based on chemical properties and physical boundaries (Fig. 2). The figure illustrates the interconnectedness of the aquifer system, and the close proximity to the wetlands.

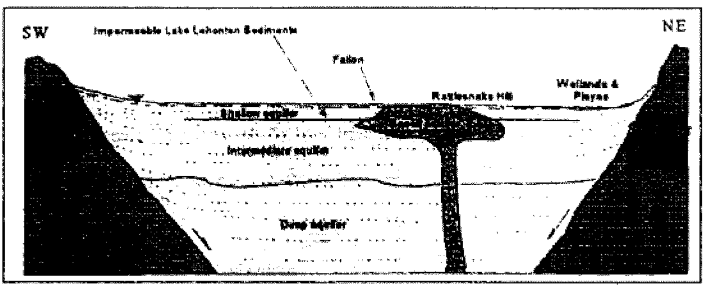

Fig. 2. Vertical Cross-Section of the Lahontan Valley Aquifer System

Three of the four aquifers are highly variable sedimentary (alluvial) formations found at shallow (0-15 m), intermediate (15-300 m), and greater (below 150 to 300 m) depths. The fourth aquifer is a mushroom-shaped basalt formation, 60-300 meters deep that is surficially exposed at Rattlesnake Hill. All four are interconnected and function as a single system, though each has distinct hydraulic and solute transport properties. The shallow aquifer is maintained by irrigation drainage.

Field, Drains and Borehole Sampling

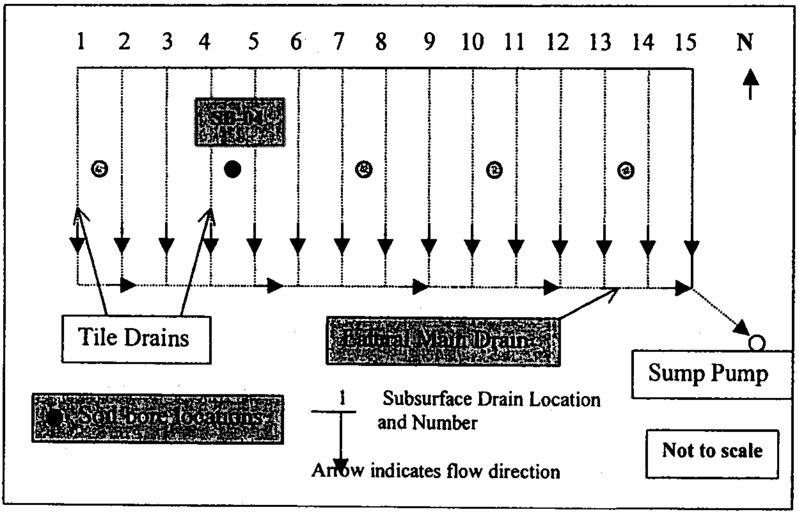

Fig. 3. Plan View of NARC Field

The study site (Fig. 3) consists of a 22-acre field, drained by a system of 15 perforated tile drains, 10 cm in diameter, spaced 37 meters apart at a 2-meter depth. The 15 drains connect to a lateral main drain that discharges into a sump. Five soil borings were drilled in the field in 1994 to average depths of 22 m. The borings were located along the east-west centerline and extended through the shallow aquifer and into the lower confining unit. Soil borings were evaluated for texture and salinity (Mathis, 1995). From the results the field depth was partitioned into 8 distinct soil layers.

Solute Transport

Salts are primarily transported with moving water. It is assumed that they do not sorb onto mineral surfaces to change their relative concentrations in the profile. Two processes for moving solutes are diffusion and advection. Diffusion occurs as waters of varying concentration mix and seek equilibrium (Fetter, 1994). Steady state diffusion follows Fick's First Law (Eq. 1), and for systems where the concentrations are changing over time diffusion follows Fick's Second Law (Eq. 2).

$$F = -D\,(dC/dx) \tag{1}$$

$$\delta C/\delta t = D\,\delta^2 C/\delta x^2 \tag{2}$$

F is the mass flux of solute ($ML^{-2}t^{-1}$), D is the diffusion coefficient (L^2t^{-1}), dC/dx is the concentration gradient ($ML^{-3}L^{-1}$), $\delta C/\delta t$ is the change in concentration over time ($ML^{-3}t^{-1}$) and $\delta^2 C/\delta x^2$ is the change in the concentration gradient.

Advection is the process by which moving water carries with it dissolved solutes. Equation 3 shows the advection form of Darcy's Law.

$$v_x = (K/\theta)\,dh/dl \tag{3}$$

The darcy velocity v_x is the average linear velocity of the water ($L\,t^{-1}$), K is the hydraulic conductivity of the medium ($L\,t^{-1}$), θ is the volumetric water content ($L^3\,L^{-3}$), and dh/dl is the hydraulic gradient. Mechanical dispersion caused by soil heterogeneity further complicates the modeling of solute transport problems. SWMS_2D (Simunek et al., 1996), the source code for HYDRUS_2D, combines three factors into the dispersion tensor, D_{ij} (Eq. 4).

$$\theta D_{ij} = D_T|q|\delta_{ij} + (D_L - D_T)q_jq_i/|q| + \theta D_d\tau\delta_{ij} \tag{4}$$

θ is the volumetric water content ($L^3\,L^{-3}$), D_T and D_L are the transverse and longitudinal dispersion coefficients (L), respectively, q is the fluid flux ($L\,t^{-1}$), τ is the tortuosity factor (–), D_d is the molecular diffusion coefficient ($L^2\,t^{-1}$), and δ_{ij} is the Kronecker delta function.

Total dissolved solids (TDS) were modeled. Electrical conductivity (EC) in $dS\,m^{-1}$ was converted to $mg\,L^{-1}$ (Eq. 5) (Bohn et al., 1985).

$$640\ EC\ (dS\,m^{-1}) = TDS\ (mg\,L^{-1}) \tag{5}$$

In HYDRUS_2D the units were converted to $cm^3\,L^{-1}$.

METHODS

The irrigation manager must balance several competing goals: minimizing water usage, drainage (both water and salts), salt accumulations in the root zone (beyond the crop's tolerance levels) and decline in quality of groundwater supplies and degradation of wetlands habitats.

Conceptual Model

The leaching fraction (LF) and leaching requirement (LR) conceptually calculate the amount of water needed beyond the plants' ET requirements for a steady state salt balance and leaching salts out of a specific crop's root zone, respectively (Eqs. 6 and 7).

$$LF = D_d / D_i = EC_i / EC_d \tag{6}$$

$$LR = D_d^* / D_i = EC_i / EC_d^* \tag{7}$$

D_d = depth of drainage water (cm) and D_i = depth of irrigation water (cm); EC_i = EC of the irrigation water (dS m^{-1}); EC_d = EC of the drainage water (Hoffman, 1990); and D_d^* is the depth of drainage based on the crop salt tolerance threshold (EC_d^*). The conversion to EC_d^* is shown in Eq. 8.

$$EC_d^* = (5\ EC_e) - EC_i \tag{8}$$

EC_e = EC of the soil water extract (dS m^{-1}).

Physical Model

Figure 4 shows a vertical cross-section of the simulated profile, with drain and piezometer locations, soil layers and boundary information. The physical model is based upon a half-drain spacing between two parallel drains, assuming a mirror image to the left of the drain (Guitjens, 1999). The half-width was 1850 cm and the half-drain size 5 cm by 10 cm. The depth of the modeled profile was 2195 cm. The soil layers reflect the bore hole information. A ninth material (loamy sand) was added around the drain to simulate the backfill material (identified in Fig. 4 as the drain box). It measures approximately 24 cm by 54 cm.

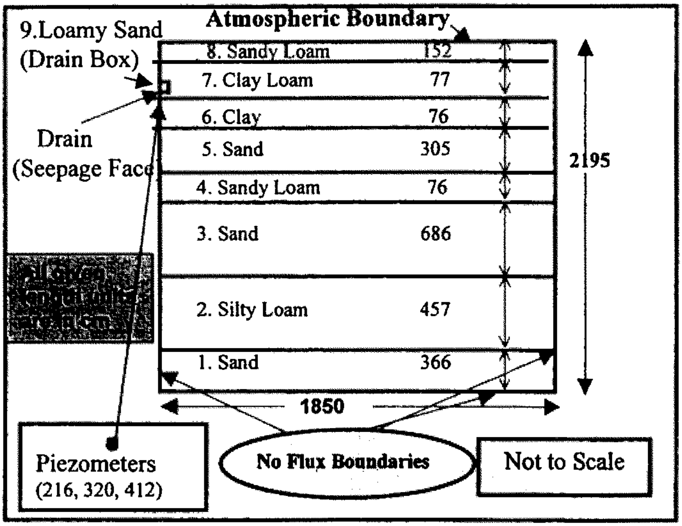

Figure 4. Soil Profile Vertical Cross-section

The mesh generator in HYDRUS_2D created a triangular element mesh composed of 3989 points, 11762 edges, and 7774 triangles. HYDRUS_2D solved the groundwater flow and solute transport equations at each node at incremental time steps.

Irrigation and evapotranspiration (ET) occurred across the surface boundary. The drain was modeled as a seepage face boundary, which allows water to move into the drain. The remaining three profile boundaries (the two vertical sides and the bottom) were designated as no flux boundaries. The left vertical boundary was chosen as no flux because it was assumed the flow paths on one side of the drain are mirror images of the flow paths on the other side of the drain. The other vertical boundary was chosen as a no-flux boundary because of the groundwater divide created by the midpoint of the flow patterns between two adjacent drains, again assuming identical conditions exist on either side of this groundwater divide.

The model simulated a root zone depth of 130 cm. Initial (t=0) pressure head distribution was based on simulating a water table at 130 cm (h = -130 cm at the surface, h = 0 cm at the 130 cm depth, and h = 2065 cm at the bottom of the profile). The pressures were linearly distributed throughout the profile. Initial profile salinity (EC_e) of the 8 layers originated from bore log data (Mathis, 1995). The observation nodes at 216, 320, and 412 cm depths below ground surface simulated the depths of the field piezometers (Pohll and Guitjens, 1994). Table 1 shows the HYDRUS_2D catalog of those soils that were identified in the 1994 bore log and the hydraulic parameters and values. The final column in Table 1 lists the layers in the soil profile.

Table 1. Soil Profile and Hydrologic Parameters

Soil Type	θ_r	θ_s	K_s (cm hr^{-1})	Profile layer
Sand	0.045	0.43	29.700	1, 3, 5
Loamy sand	0.057	0.41	14.592	9
Sandy loam	0.065	0.41	4.421	4, 8
Clay loam	0.100	0.39	1.310	7
Silty loam	0.034	0.46	0.250	2
Clay	0.070	0.36	0.020	6

The default HYDRUS_2D values for the Feddes Root Water Uptake Parameters were changed to allow water to be fully taken up by plant roots and thereby allowed the simulations to run to completion.

Irrigation Schedule

A one-year irrigation and ET schedule was put into a time-variable boundary record (TVBR) table of HYDRUS_2D. For the growing season, March 16-October 11, time steps of 12 hours allowed the depths of evapotranspiration, irrigation and natural precipitation (D_{et}, D_i and D_r, respectively) to be evenly spread over 12 hours, the ET occurring during daylight hours. The dormant season, October 12-March 14, began at t =5148 hours. Time steps of 168 hours allowed the weekly D_{et} and D_r to be evenly spread over 168 hours. The final day of the dormant season, March 15, completed the full-year schedule, for a total of 8868 hours. The concentration of the irrigation water (C_i) was initially set at 0.25 mg cm^{-3}. The D_{et} was based on Eq. 9 (Guitjens, 1987). Reference ET (ET_o) values were based on measured Class A pan evaporation adjusted for wind speed and relative humidity.

$$D_{et} = K_{crop}\, ET_o \qquad (9)$$

Site-specific crop coefficients (K_{crop}) were from Guitjens (1987). The TVBR consisted of 446 time periods for a 5148-hour growing season schedule.

Model Calibration and Sensitivity Analysis

The model was calibrated to the piezometer data of Pohll and Guitjens (1994). Calibration was accomplished by comparing field and modeled-output pressures. Hydraulic parameters of layers 6, 7 and 8 (those closest to the drain) were adjusted to obtain an acceptable agreement. After calibration, a sensitivity analysis was performed to determine the response to changes in D_i and D_{et}. The "best" schedule for meeting the ET allowed for approximately a 25% LF and became the basis for all subsequent simulations of management alternatives.

Management Scenarios

In order to minimize drainage effluent and mass salt flux in the drainwater, four alternative irrigation management practices were considered. The management alternatives included varying D_i and C_i.

Table 2. Management Alternatives and Initial Conditions

Mgmt.				Initial conditions (I.C.) (mg cm^{-3})		
Alt. (#)	C_i (mg cm^{-3})	D_i (ratio)	C_{sw} (mg cm^{-3})	Layer 8 G.S. to 152cm	Layer 7 153 to 229cm	Layer 6 230 to 305cm
1	0.25	1.00D_i	I.C.	0.576	0.768	0.640
2	2.50	1.00D_i	I.C.	"	"	"
3	0.25	0.75D_i	I.C.	"	"	"
4	2.50	0.75D_i	I.C.	"	"	"

For example, the first irrigation application of the season (at t=324 hrs.) was 22.86 cm; this amount exceeded the D_{et}, the remainder going to D_d. To decrease drainage D_i was multiplied by 0.75, yielding 17.15 cm.

RESULTS AND DISCUSSION

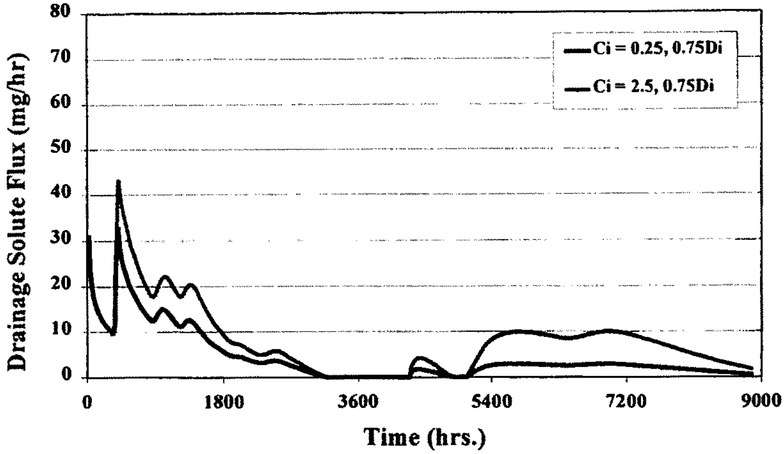

Fig. 5. Drainage Solute Flux for $C_i = 0.25$ and 2.50 mg cm^{-3} and $0.75D_i$

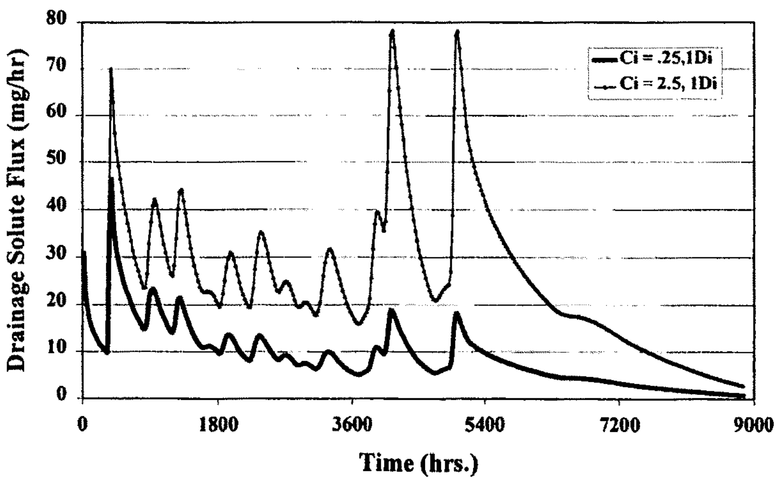

Fig. 6. Drainage Solute Flux for $C_i = 0.25$ and 2.50 mg cm^{-3} and $1.00D_i$

Figures 5 and 6 illustrate the effects of C_i and D_i on the drainage solute mass flux. Comparing Figs. 5 and 6, the $1.00D_i$ increased the drainage solute flux and the peaks at irrigation events. Furthermore, the effect of $C_i = 2.50$ was very pronounced. Fig. 7 shows the changes in C_{sw} at the beginning of the season (t=0 hrs.), at the end of the growing season (t=5148 hrs.) and at the end of the year (t=8800 hrs.) for two D_i levels. More leaching occurred for $1.00D_i$. The concentrations in the unsaturated zone are also affected by the water content.

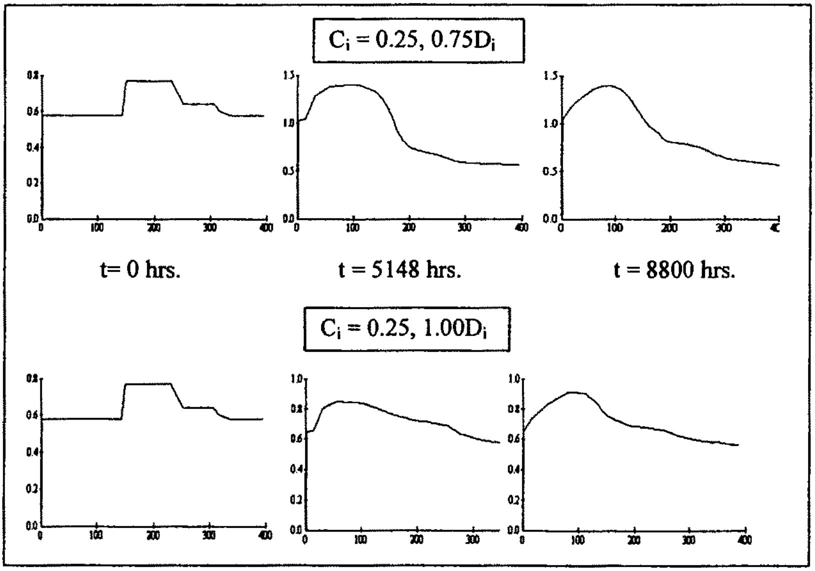

Fig. 7. C_{sw} along a line 18 cm parallel to the left vertical boundary from the soil surface to a depth of 400 cm, for $0.75D_i$ and $1.00D_i$, at $C_i = 0.25$ mg cm^{-3}, at t = 0, 5148 and 8800 hrs.

The same trend also occurred when C_i was increased to 2.50 mg cm^{-3} (Fig.8). These trends follow the trends of Rhoades and Loveday (1990).

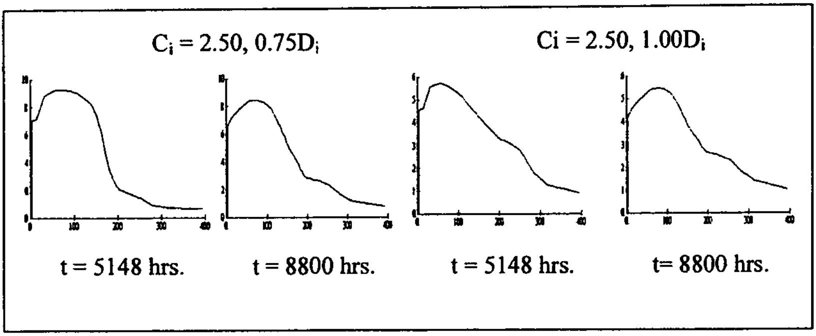

Fig. 8. C_{sw} along a line 18 cm parallel to the left vertical boundary from the soil surface to a depth of 400 cm, for $0.75D_i$ and $1.00D_i$, at $C_i = 2.50$ mg cm^{-3}, at t = 5148 and 8800 hrs.

Figure 8 shows similar trends for $C_i = 2.50$, but note the dramatic increase in C_{sw}. After just one season of applying saline water ($C_i = 2.50$), the salinity in the root zone was high enough to reduce the yields of most alfalfa crops by 80% or more (Rhoades and Loveday, 1990).

CONCLUSIONS

HYDRUS_2D was used to demonstrate the effects of management changes in irrigation quantity and salinity on solute flux and the salt distribution in the upper soil profile. This approach differs from the concepts LF and LR. HYDRUS_2D, a physically-based model, provides a simulation technique that allows more realistic manager-control of drainage quantity and salinity.

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MANAGEMENT OF WATERLOGGED SALINE SOILS AND STRATEGIES TO MINIMIZE PROBLEMS OF DRAINAGE EFFLUENT DISPOSAL

S. K. Gupta

ABSTRACT

Expansion of irrigation to arid and semi-arid regions through inter basin transfer of water together with research and development in agriculture were instrumental to tide over the food scarcity crisis in the country. The expansion based on inter basin transfer of water, however, led to adverse environmental impacts. Within 10-15 years of operation of the projects, conditions of waterlogging and soil salinization appeared in many irrigation projects. The present paper highlights the causes of waterlogging and soil salinity in irrigation commands with reference to the projects in the Gujarat and Karnataka States of India. Amongst the various factors, inadequate drainage ranks as number one cause for the development of waterlogging in the commands. In the monsoon climatic conditions as prevails in India, surface drainage seems to be essential although it may not be able to control the water table. The paper also deals with the attempts being made in various irrigation commands to establish the feasibility of subsurface drainage for the reclamation and management of waterlogged salt affected soils. Some of the major findings are discussed to show that drainage cost in monsoon climatic conditions could be substantially reduced over the conventional designs applicable to humid climatic regions. In recent years, it has been seen that drainage effluent disposal could be a serious issue in planning drainage programs. Present paper highlights the water quality issues in India under various kinds of drainage systems. Drainage design issues (depth, spacing and bi-level drainage) and operational schedules that help to minimize generation of drainage effluent have been discussed. Direct and conjunctive use strategies have been highlighted to show that reuse of poor quality drainage effluent near to the generation sites is feasible. Mathematical models have been used to show that such a strategy would be sustainable on a long term basis. It is argued that an approach based on these two strategies in combination would make the drainage system cost effective and eco-friendly.

INTRODUCTION

Irrigation is the most effective means of increasing and stabilizing agricultural production in areas where rainfall is erratic and inadequate to meet the crop consumptive requirements. India, therefore, decided to make huge investments in

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Water Resources Development (WRD) to expand its irrigation network. It also invested heavily in agricultural research and technology development. Such a strategy paid rich dividends. We entered the most spectacular green revolution ever witnessed and became self sufficient in food production. Lately, the irrigation sector has come under attack because the productivity has not increased as much as it was expected.

Appearance of adverse environmental impacts have created doubts on the sustainability of irrigated agriculture. It has also emboldened the environmentalists to urge some rethinking on further investments in the major and medium sectors of irrigation development. According to a report of the working group set-up by the Ministry of Water Resources, it is assessed that as much as 5.86 million ha of irrigated land has been affected by the twin problems. Thus, huge investments made in developing irrigation potential for these lands are locked. Besides, annual losses on account of interest on this investment, loss of crop production sums up to several thousands crores (1 crore=10 million and 1 US $ = Rs. 43) of rupees.

DRAINAGE: THE KEY FACTOR

Rise in water table is an inevitable consequence of surface irrigation through inter-basin transfer of water. Several factors together determine the rate at which water table would rise in a given setting. Some of these factors are common to many irrigation commands while few others are site specific and would be applicable only to specific commands. Amongst the common factors, inadequate drainage and poor maintenance of the drainage systems can be cited. As per the information supplied by the states to the working group, inadequate drainage has been cited as one of the reasons for the development of waterlogging. On the other hand, drainage improvement has also been suggested as a remedial measure for the amelioration of the problems of waterlogging and soil salinity (Report Working Group, 1991). The states which have given these reasons are: Andhra Pradesh, Haryana, Karnataka, Madhaya Pradesh., Bihar, Maharashtra, Punjab, Tamil Nadu and Uttar Pradesh. Attempts have been made in the past to determine and rank various factors/processes that are responsible for waterlogging and soil salinity in irrigation commands (Table 1). Amongst various factors, inadequate drainage takes the first rank in irrigation commands of the Karnataka and the Gujarat states (Reddy, 1991; Gupta and Khandelwal, 1996).

DRAINAGE ALTERNATIVES

Most common techniques to drain excess water are: A) Surface drainage and B) Subsurface drainage. Subsurface drainage could be achieved through i) horizontal subsurface drainage, ii) Tube well or vertical drainage. Many local alternate solutions to drain the lands have been identified but the basic principles of these alternate techniques have been derived from one of the three alternatives.

Table 1 Response to Factors Leading to Waterlogging in Irrigation Commands

Reason	Weighted rank in Ukai-Kakrapar (%)[1]	% respondents in Commands[2] in Karnataka
Inadequate drainage	74.1	100
Seepage and leakage	66.7	-
Excess water	65.6	-
Poor maintenance of drainage system	61.7	92
Change in cropping pattern in favour of waterloving crops	60.4	82
Poor on-Farm W.M.	56.0	46

- Not responded [1] Source: Gupta and Khandelwal (1996)
[2] Source: Reddy (1991)

Surface Drainage

The surface drainage problem is most commonly associated with humid regions. However, in monsoon climatic condition as are prevalent in India, problem of surface drainage could be experienced even in the arid and the semi-arid regions. The problem may be quite serious in regions where average annual rainfall exceeds 500 mm. Analysis of daily rainfall data reveals that there are ample opportunities for water stagnation to occur in crop lands (Table 2). The unfavorable soil characteristics and flat topography may accentuate the problem. As the water table in irrigation commands rises, the absorption of water is reduced, so that the depth of stagnation and the duration for which stagnation occur also increases. For example; in the semi-arid region of Haryana, it is not uncommon to see pools of water for prolonged periods in areas with shallow water table. Rain water stagnation by more than one day could be experienced from storms of 5 year return period (Rain storms expected to occur once in five years i.e at a probability of 20 %). With storms of 10 year return period, the stagnation might continue for 3 days or more (Rao et al., 1994). Surface drainage requirements also depend upon the crop characteristics.

Degree of drainage required, therefore, could to some extent be manipulated through selection of crops. (Gupta et al. 1992) collated the available information on this aspect and determined the relative tolerance of some crops (Table 3). The data reveal that sunflower, cotton and wheat on normal lands are relatively more tolerant than other crops. Benefits of surface drainage have been reported by many workers particularly in heavy soils. The data from the Ukai-Kakrapar command reveal that by preventing surface stagnation for prolonged periods, yield improvement to varying degrees could be obtained (Table 4).

Table 2 Storm Rainfall of Various Duration at Different Probabilities

Station climate (Rainfall mm)	Duration (days)	Storm rainfall (mm) at % probability				
		10	25	50	75	90
Hisar, arid (375)	1	64	39	25	18	11
	2	102	75	60	42	39
	3	119	93	75	60	52
	4	135	110	81	78	62
Ludhiana semi-arid (681)	1	178	145	95	58	42
	2	220	179	116	69	50
	3	232	189	125	77	56
	4	237	195	132	85	66
Cuttack sub-humid (1514)	1	198	167	128	85	70
	2	275	229	173	109	87
	3	293	246	188	123	101
	4	312	264	205	138	115
Dapoli humid (3372)	1	363	309	227	166	140
	2	530	463	362	286	254
	3	623	555	452	376	342
	4	719	641	523	435	398

Table 3 Relative Tolerance of Crops to Surface Stagnation of Water

Threshold (t) (hrs)	Crops
0<t<12 (1 day)	Wheat (A), Groundnut Maize (*), Potato Green peas, Mustard
12<t<36 (1 to 2 days)	Pigeon pea, Cow pea, Barley(A)
36<t<60 (2 to 3 days)	Wheat(N), Beets, Forage Sunflower, Cotton

Threshold value indicate that if water stagnation does not exceed this value, there would be no decrease in the yield. Beyond this the crops would be adversely affected.
A=semi reclaimed alkali soils
N=normal soils
* at the most sensitive stage

Table 4 Yield Increase in Crops Achieved following Improvement in Surface Drainage

Crop	Yield improvement (% over poorly drained)
Sugarcane	19.1-27.7
Paddy	19.7-24.7
Gram	32.1
Indian bean	49.8

A group of engineers/planners believes that surface drainage is a panacea for all the ills of the irrigation commands in India. No doubt, problems to some extent could be traced to inadequate surface drainage; yet it has been shown beyond doubt that water table rise has occurred unabated even in areas where surface drainage has been provided. Surface drainage could reduce the rate of rise of the water table but can not prevent its rise altogether. Experiences have also revealed that surface drainage alone is not helpful in the reclamation of waterlogged saline lands. Reclamation of salt affected soils through leaching alone was not successful on a sustainable basis. A crop of wheat could be grown with rain water management during the monsoon season followed by leaching before the sowing of wheat. The following *kharif* crop could not be grown successfully due to salt accumulation in the root zone due to secondary soil salinization during the summer season (Gupta, 1983). A surface drainage system installed at Mooraj in the Mahi-Kadana command failed to reclaim the waterlogged saline land. The system was, therefore, converted to a subsurface drainage system after 2 years of operation (Singh and Kumbhare, 1987). In RAJAD project in the Chambal command of Rajasthan, leaching in the controlled plots is reported to be less than 5 percent. Drainage improved the leaching pattern substantially and with surface drainage 20-22 percent of salts could be leached. But it failed to reclaim the land over a 1.5 year period (Tyagi et al. 1996).

From the foregoing, it seems that provision of surface drainage has to be made in most areas especially in humid, sub-humid and semi-arid areas. The surface drainage has to be an integral part of any water management or drainage plan. The cost of the system could be partially recovered as it helps to reduce the cost of subsurface drainage.

Subsurface Drainage

Subsurface drainage could be accomplished either with vertical or horizontal drainage. Our past experience with vertical drainage has been quite good so much so that many people think that this technology could be extended to waterlogged salt affected areas. The extension of this technology to such areas is subject to availability of good aquifers and quality of water. As a result of these limitations the progress of vertical drainage has been abysmally slow.

Horizontal Drainage: Sporadic experiments on horizontal drainage have been conducted in this country since the beginning of this century but concerted efforts have only been made during the last two decades. Well investigated and scientifically laid out systems have generated data on the usefulness of this technology to control water table in the pre-decided range as well as in helping to leach down the salts. The horizontal subsurface drainage is most suited to control water table in humid regions, in arid and semi-arid regions where water table in the month of June is within 2 m of the ground surface and is of poor quality, disposal outlets are limited and to reclaim highly salt affected soils where other kinds of drainage may not suit or may take longer time to leach down the salts.It appears at this stage that there are no doubts about its technical feasibility (Table 5).

The important questions agitating the researchers and planners however has been its initial cost and problems related to drainage effluent disposal. Thus, research efforts are directed to obtain general as well as site specific solutions to the problems so as to minimize the cost of the drainage systems. Mole drains, chimney drains, brick, bamboo and gravel drains (The last three names derived on the basis of material used for drains) have been designed as a result of these efforts. These alternatives could help to reduce the cost. Improved design criteria

Table 5 Benefits of Subsurface Drainage for Reclamation and Crop Production at Sampla

Particulars and years after installation	Reclamation and crop yield in drain spacings (m)		
	25	50	75
Soil EC_e (0-15)			
0 year	52.2	59.4	49.5
10 years after	4.7	4.7	4.9
Crop yield (t/ha)			
0 year	0.0	0.0	0.0
10 year average	4.9	4.4	4.0

Table 6 Cost of Different Drainage Systems

Drainage Technique	Cost (Rs./ha)
Surface drainage	7,000-10,000
Sub-surface drainage	20,000-30,000
Vertical drainage[1]	5,000- 7,500 +Rs 100,000/annum
Bio-drainage[2]	11,000

[1] The lower value of cost/ha with the assumption that tube well serves an area of 5 ha.The value shown separately with plus sign is the operational and maintenance cost of a government tube well.
[2] It includes maintenance for 2 years and surface drainage cost. (Cost as per UPLDC (1991) document excluding the cost of gypsum)

are also being developed to reduce the cost. The cost of an integrated drainage system would be much less than a single drainage system. An idea of the cost of individual drainage systems could be had from the data on cost provided in Table 6. We have sufficient data and expertise to achieve this kind of integration. There is also a need of an unified apex organization that could integrate the activities such as monitoring of the problems, plan measures for prevention, take up surface or subsurface drainage works and undertake reclamation of saline/alkali lands. A major limitation in this kind of drainage seems to be the disposal of drainage effluent as it might cause adverse environmental impacts. Studies are underway to develop technologies for minimizing return flow, (re)use of drainage effluents and disposal through various means including evaporation tanks and bio-drainage (Gupta, 1998).

STRATEGIES TO MINIMIZE DRAINAGE EFFLUENT

On-farm Water Management

Introduction of irrigation has generally created an imbalance between the recharge and discharge to the aquifer. As a result water has been taken into storage that led to the rise in the water table in the irrigation commands. Leakage and seepage from the system components and poor on-farm water management are often cited as contributing factors to this development. It is estimated that project efficiencies are as low as 30 percent. The state of affairs could also be visualized from the fact that at many places field to field irrigation is still practiced although more than 20 years have elapsed when the irrigation was introduced. Thus, the most cost effective approach to reduce drainage discharge could be to incorporate a fairly good degree of on-farm water management practices that reduce seepage and deep percolation losses. Technically feasible and cost effective measures could be lining of water courses, scientific irrigation scheduling, improved control and measurement of irrigation water, land leveling, proper design of conventional irrigation system or switch over from traditional to improved irrigation methods. Besides these, participatory irrigation management and pricing of water to recover at least the cost of operation and maintenance could help improve on-farm water management. The potential of these practices in improving irrigation efficiencies has been demonstrated widely in India, yet the implementation is subject to a wide range of economic, institutional, environmental and social constraints.

Drainage System Design and Operation

For sustained irrigated agriculture, drainage improvement is the key element. In the Indian context, however, improvement in drainage is required only for short critical period of time during a year (mostly the monsoon season). Thus, there could be several drainage system designs, which can be utilized to satisfy agricultural requirement. The drainage systems can also be managed through operational schedules, which could have a bearing on the quality of drainage effluent or the salt load.

Drainage Coefficient or Drainage Design Criterion: In the design of the subsurface drainage system, drainage coefficient determines the amount of discharge that would be expected during the operation of the system. Thus, an accurate estimate of the drainage coefficient would not only help to reduce the drainage effluent but would also reduce the cost of the drainage system. It has been seen that a drainage coefficient calculated on the basis of water during the monsoon season would help to maintain the water table as well as ensure sufficient leaching. As an example, a drainage coefficient of 1.5 mm/day was worked out on the basis of this approach. For the same site, one would arrive at a drainage coefficient of 5.5 mm/day if leaching of salts from the upper 60 cm soil profile is taken as the criterion to assess the drainage coefficient. It may be noted that former value is less than 1/3 of the later.

Even under non-steady state conditions, a more conservative drainage design criterion could be adopted. The commonly used criterion in India states that water table be lowered to 30 cm below the ground surface in 2 days time once the water table reaches at the soil surface. Studies at one of the experimental site (Sampla, Haryana, India) for alluvial soils have revealed that in a system where lateral drain spacing lowered the water table in 2.5 days time, average yield of 90 % could be obtained over a 10 year period time (Gupta et al. 1998). There was little difference in salt leaching except during the first few years (Table 7). Experiences at other places have also shown that drains could be spaced farther apart compared to the conventional design criterion.

Table 7 Relative Salt Leaching (Top 60 cm Profile) in Plots With Different Drain Spacing (System Installed in 6/84)

Drain spacing (m)	Fraction of salt leached in month/year							
	10/84	3/85	4/86	11/86	6/87	11/87	4/90	6/95
25	0.66	0.85	0.89	0.87	0.88	0.85	0.93	0.91
50	0.45	0.69	0.78	0.88	0.78	0.76	0.87	0.92
75	0.36	0.36	0.60	0.74	0.66	0.65	0.84	0.90

Operational Schedules: Shallow water table may not always be a curse. Most crops are capable of drawing water from the shallow water table to meet their consumptive use requirement. The direct water use by the crops from the shallow water table could be aided by withholding irrigation or following what is usually called a deficit irrigation schedule. It could also be achieved by withholding water towards the end of the crop season (say by skipping the last irrigation). Such a strategy not only helps to reduce the irrigation water requirement of the crops but also reduces the drainage effluent. Experience in India have shown that once the water table approaches 1 m depth, pump operation could be so scheduled that water table remains at or around this depth. Any drainage at this depth could occur under natural conditions. The data reveal that with this strategy, yield with a water expense of 245 mm is nearly the same as with an expense of 355 mm (Table 8). Thus, one could save about 2 irrigations provided water is maintained at about 1.0 m depth.

Bi-level Drainage: The strategy to withhold water table at about 1 m depth has been found beneficial in aiding the uptake of water by the crops. In addition to what has been stated in the foregoing paragraph, another way to achieve the same objective could be through the installation of bi-level drains. A bi-level drainage system is a system of horizontal drains in which two adjacent drain lines are laid at two different elevations or levels on an alternating basis. A line laid at relatively shallow depth (1 to 1.2m) is followed by a line at relatively deeper depth (1.5 to 1.8 m). It may be noted that the discharge from a bi-level drainage system once the water table reaches the shallow drain depth is much less than the conventional drainage system for the same drain spacing (Table 9). It is nearly equal to the discharge from drains spaced at double the spacing.

Table 8 Effect of Groundwater Salinity and Water Expense on Wheat Yield at Sampla

Water expense (mm)	Yield* (t/ha)with ground water salinity (dS/m)			
	3.0	5.5	20.0	Mean
135	4.55	3.20	2.45	3.55
190	4.95	4.70	3.85	4.50
245	5.45	4.45	5.05	5.00
300	5.50	4.80	4.85	5.05
355	5.30	4.85	4.90	5.00

* Average of 2 years; Source: Rao et al. (1992).

Table 9 Comparison of Discharge Rate from Deep Drain in a Bi-level and a Level Drainage System

	Spacing (m)	Discharge per unit length (h_o=1.8 m & h_l=0.6 m)	Discharge per unit length (*h_o=1.5 m & h_l=0.3 m)
Bi-level	50.0	0.14	0.06
Level	50.0	0.23	0.11
	100.0	0.12	0.05

Source: Verma et al. (1998)
*h_o is the depth of the relatively deep drain while h_l is the difference between the elevations of the two drains.

Integrated Drainage System

The importance of surface drains in fields where subsurface drainage has been implemented is often misunderstood. It is more so when the purpose of drainage is to reclaim the salt affected lands. Under these conditions, it is believed that most of the rainfall should be stored in fields with dykes of appropriate height and allowed to drain through subsurface drains to facilitate leaching of salts. It may be true in the first one or two seasons but later on the depth and duration of storage has to be commensurate with the tolerance of the crop to water stagnation. The surface drains should be designed on this basis as it would help to reduce the recharge to the groundwater as well as reduce drainage discharge to the extent water is removed by the surface drains.

It may be mentioned that implementation of an integrated drainage system combining surface/subsurface drainage would not only influence the time distribution of the water flow from the fields but also the salt loading. Usually surface run-off waters are of relatively better quality than subsurface drainage effluents (Table 10). The data reveal that the former could be directly used for most crop combinations. Moreover, surface run-off could usually be drained by gravity. Thus, the problems of drainage water disposal would be much less than with the drainage effluents from subsurface drains.

Table 10 Average Chemical Composition of Water from Various Sources in Haryana

Water	EC (dS/m)	SAR	Solute concentration (me/L)			
			Ca+Mg	Na	HCO_3	Cl
Canal water (Western Jamuna canal, Sampla)	0.70	0.80	2.00	0.8	2.00	0.80
Drain No. 8 (Gohana)	0.55	2.24	2.60	2.56	2.55	1 80
Subsurface drainage water (Sampla)						
1986-87	26.50	16.80	173.00	156.00	1.80	315.00
1989-90	15.00	14.50	126.00	115.00	1.60	221.00

Source: compiled by Gupta and Gupta (1997)

Reuse Strategies

Reuse of drainage effluents at a place nearest to its generation is probably the best way to avoid problems related to its transportation and disposal to natural drains. It should be possible to reuse saline drainage effluents either directly or in conjunction with fresh water depending upon the quality of the drainage effluent. Choice of crops and choice of an irrigation method could help to widen the reuse alternatives.

Selection of Crops: Intragenic and intergenic differences in salt tolerance of crops could be exploited to use the saline drainage effluents. Usually grasses and forest trees are more tolerant to salts than many arable crops. Most tolerant being some of the halophytes. Thus, to widen the range of salt tolerance, these species could be considered and grown on some parcels of lands. These parcels of lands could be solely irrigated by saline water. Sequential application of drainage water to cereal crops, grasses, forest plantations and halophytes could be used to concentrate and reduce the saline drainage effluents for disposal. Although, such a complex system may not be needed at present, its potential may be kept in view for future research studies.

Irrigation Methods: The effect of saline environment on crop growth is basically due to the combined effect of matric and the osmotic stresses. To minimize the adverse effects due to osmotic stress, one could manipulate the matric stress (minimize) to get good crop yields under saline environment. A irrigation method by which one could apply shallow but frequent irrigation would be helpful in minimizing matric stress. Evidences have been generated to show that with sprinklers and drip irrigation, relatively more saline waters could be applied than with surface irrigation. A pitcher irrigation technique developed at CSSRI, Karnal has been successfully used to grow even sensitive crops with saline waters (Table 11).

Table 11 Irrigation water salinity for equivalent yield as that with fresh water

Crop	Irrigation water salinity (dS/m)
Tomato	5.7
Brinjal	9.8
Cauliflower	15.0
Ridge-gourd	3.2
Cabbage	9.7
Water melon	9.0
Musk melon	9.0
Grapes	4.0

Source: Dubey et al. (1991)

<u>Conjunctive Use</u>: Without doubt, surface irrigation would continue to dominate Indian agriculture for the next few decades. Thus strategies which would allow use of saline waters with surface irrigation would have a greater potential of their application. Conjunctive use of surface (fresh quality) and poor quality waters through blending or cyclic application could be employed to minimize adverse effects of poor quality ground waters on land and water resource. It would allow to achieve yield potentials which are nearly equal to the one attained with fresh water alone.

Both the blending and cyclic use strategies have been adopted for reuse of drainage waters (Sharma et al. 1991). Practically speaking, blending is useful in cases when fresh and drainage water qualities are such that mix water would have salinity less than the threshold salinity up to which there is no yield reduction of a given crop. In other cases cyclic use strategy would be more beneficial.

Notwithstanding the salinity build - up in the soil profile in conjunctive use, the monsoon climatic conditions that are prevalent in India, favor the adoption of cyclic use strategy. More than 80% of the salts accumulated in the root zone during the winter season are leached down the profile during the monsoon season. Thus, the root zone becomes fit for cultivation and recycling of the drainage effluent. Model studies have also revealed that some accumulation of salts may occur on annual basis in years when the monsoon season rainfall is below the average. However, above average rainfall years helps to maintain the salt balance in the root zone over the long run. Thus, one could overlook the salt accumulation over a season or even during an abnormal year (Below average rainfall year).

CONCLUDING REMARKS

Reclamation and management of waterlogged salt affected soils seems to be the key element in generating confidence on the sustainability of irrigated agriculture in the country. The inevitability of drainage is now being realized at different levels. It seems that the cost of drainage and the huge investments that are needed are the biggest impediments in implementing drainage plans. As much as 20-25 million tonnes of food grains could be produced as a result of reclamation of these lands in irrigation commands. An integrated drainage system with surface and horizontal pipe drainage seems to be one of the most appropriate strategy to reclaim the lands already affected by waterlogging and soil salinity. Although technical and economic feasibility of the system has been established, disposal of drainage effluent seems to be still a critical issue. For this purpose, several strategies have been described. It is, however, visualized that no single strategy would be able to solve the problems. Since most drainage water may not have lost their potential for reuse, we are optimistic that strategies, which reduce the drainage discharge together with its reuse could help plan the effluent disposal in a far better manner then without these strategies.

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MOST ASKED QUESTIONS ABOUT GEOSYNTHETIC CANAL LININGS DO THEY WORK? AND HOW MUCH DO THEY COST?

Jack Haynes[1]

ABSTRACT

The Bureau of Reclamation (Reclamation) is collaborating with several irrigation districts in central Oregon to demonstrate and evaluate various canal linings under actual field conditions. This paper shows the results of more than 7 years of field testing and includes a series of photographs showing the subgrades, construction, and required maintenance. This paper also examines the effectiveness of the various geosynthetics and other materials to control seepage and compares construction costs.

Uncontrolled field testing of 29 types of geosynthetic canal liners exposed the various materials to very harsh conditions including freeze/thaw, wet/dry, direct and indirect sunlight, extreme rocky subgrades, wildlife (elk, deer, rodents, cattle, etc.) and man. Canals in this study had fractured basalt bottoms and typically lost 35 to 50 percent of the flow to seepage. Pre-construction seepage rates as determined by full-scale ponding tests ranged from 0.6 to 4.2 ft^3/ft^2-day. Following the installation of the linings, average seepage rates were reduced to less than 0.1 ft^3/ft^2-day.

BACKGROUND

This paper describes the Deschutes Canal Lining Demonstration Project. To date, 29 test sections have been constructed on seven irrigation districts. The lining materials include combinations of geosynthetics, concrete grout, shotcrete, and elastomeric coatings. The test sections are being evaluated for durability and effectiveness in reducing seepage. The test sections now range in age from 6 months to 8 years, and the differences in performance are becoming apparent, see table 1.

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Table 1. - 6½ Year Condition Assessment and Construction Costs

	Test Section Description	Cost $/ft²	Condition (age)	Comments
A-1	Polyethylene Geocomposite with 3-in Shotcrete cover	$2.06	Excellent (7 years)	No problems
A-2	30 mil VLDPE with 3-in Shotcrete cover	$2.14	Excellent (6½ years)	No problems
A-3	Exposed 80 mil HDPE	$1.38	Very good (6½ years)	Several small tears and cuts
A-4	Exposed PVC Geocomposite	$1.05	Very good (7 years)	Several small tears and cuts Unbonded geotextile seams
A-5	Exposed 45 mil CSPE	$1.11	Very good (7 years)	Several small tears and cuts
A-6	Exposed 36 mil CSPE Geocomposite	$1.03	Very good (7 years)	Several small tears and cuts
A-7	40 mil PVC with 3-in Grout-filled mattress	$2.36	Excellent (7½ years)	No problems
A-8	3-in Grout-filled Mattress	$1.86	Excellent (7 years)	No problems
A-9	Exposed 60 mil VLDPE with Grout-filled Mattress on Side Slopes only	$1.79	Removed from Study after 28 months	Liner "whales" were impeding flow
A-10	Exposed 60 mil HDPE with Grout-filled Mattress on Side Slopes only	$1.79	Removed from Study after 28 months	Liner "whales" were impeding flow
N-1	SPUF with Urethane Protective Coating	$4.33	Poor (6 years)	Partial Foam wash-out, Invert replaced with RCC
N-2	SPUF with modified Urethane Protective Coating	$3.92	Poor (6½ years)	Partial Foam wash-out, Invert replaced with RCC
N-3	Woven Geotextile with modified Urethane Coating	$2.64	Failed (1st day)	Complete Failure (May 1993)
N-4	Needle-punched Geotextile with modified Urethane Coating	$2.64	Failed (1st day)	Complete Failure (May 1993)
N-6	3-in Shotcrete with steel fibers	$1.59	Excellent (7 years)	No problems
N-7	3-in Shotcrete with Polyfibers	$1.47	Excellent (7 years)	No problems
N-8	3-in Shotcrete with fibrillated Polyfibers	$1.47	Excellent (7 years)	No problems

	Test Section Description	Cost $/ft²	Condition (age)	Comments
N-9	3-in Unreinforced Shotcrete	$1.33	Excellent (7 years)	No problems
T-1	Neoprene-Asphalt Emulsion over an Existing Concrete Flume	$1.70	Poor (5 years)	Tore away from Invert. Removed from study
T-2	Neoprene-Asphalt Emulsion over a Sandblasted Steel Flume	$2.16	Very Good (5 years)	40-50 blisters in the Invert
T-3	Neoprene-Asphalt Emulsion over a Broomed Steel Flume	$1.40	Very Good (4 years)	About 40 blisters in the Invert
L-1	Exposed 160 mil Bituminous Geomembrane	$1.39	Very Good (5 years)	Partial wash-out has been repaired
J-1	Exposed 160 mil Bituminous Geomembrane	$1.39	Excellent (1½ year)	
O-1a	Covered Geosynthetic Clay Liner	$0.82	Excellent (1 year)	
O-1b	Covered Geosynthetic Clay Liner	$0.87	Excellent (1 year)	
O-2a	Exposed Geosynthetic Clay Liner	$0.76	Very Good (1 year)	Some curling of exposed edges
O-2b	Exposed Geosynthetic Clay Liner	$0.81	Very Good (1 year)	Some curling of exposed edges
O-3a	Exposed 45-mil EPDM with 8-oz geotextile on sideslopes only	$0.84		New
O-3b	Exposed 45-mil EPDM with 8-oz geotextile on sideslopes only and covered invert	$0.87		New
O-4	Exposed 30-mil LLDPE with 8-oz geotextile on sideslopes only	$0.78		New
F-1	Exposed 45-mil Reinforced Polypropylene	$0.90	Excellent (1 year)	
N-5	Roller-Compacted Concrete Invert only	$2.00	Excellent (2 year)	

Geology

Oregon's volcanic geology contributes to high seepage rates (Gilbert, 1991), and canals in the area typically lose 35 to 50 percent of their water to seepage because they have fractured basalt bottoms (Fig. 1) and/or sides of highly porous soil, or soil and rock (Fig. 2). The fractured basalt subgrade also hinders excavation in the canal prism. Therefore, specialized lining technologies are needed to reduce seepage in these areas. Subgrade conditions for the one test section in Oklahoma were mostly fine sands with some gravel.

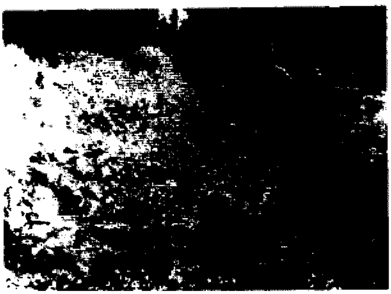

Fig. 1. Basalt Subgrade

Fig. 2. Invert Sediment

Ponding Test Results

Both pre- and post-construction ponding tests were conducted to determine seepage rates on the Arnold and on the North Unit test sections. Pre-construction seepage rates as determined by full-scale ponding tests ranged from 0.6 to 4.2 ft^3/ft^2-day (Swihart, 1994). Following the installation of the linings, average seepage rates were reduced to less than 0.1 ft^3/ft^2-day (Burnett, 1997). Additional tests are planned for inclusion in the final report.

Test Section A-1 - Polyethylene Geocomposite with 3-inch Shotcrete Cover

Const. Cost = \$2.06/ft^2; L = 1,000 ft; A = 30,000 ft^2

Condition: Excellent - After almost 6 years service, the shotcrete lining is in excellent condition, completely protecting the underlying Petromat geosynthetic liner from weathering and mechanical damage (Fig. 3). The only significant damage is that the shotcrete cover is showing extensive cracking over the anchor trench where the shotcrete was tapered-down to a thickness of less than 1 in (Fig. 4). Tapering of the shotcrete over the anchor trench is not recommended for future installations; instead the shotcrete should maintain a minimum thickness of 2 inches over the anchor trench.

Maintenance: Minimal maintenance required to date.

Fig. 3 - Overview of both A-1 and A-2

Fig. 4 - Cracking over anchor trench at top

Test Section A-2 - 30-mil textured VLDPE with geotextile cushion & 3-inch Shotcrete Cover

Const. Cost = \$2.14/ft^2; L = 500 ft; A = 15,000 ft^2

Condition: Excellent - After 5½ years, the shotcrete lining is in excellent condition, completely protecting the underlying VLDPE geosynthetic liner (Fig. 3). Dozens of transverse contraction cracks have developed on each bank. Some new cracks appear every year, and many of the old cracks grow in length, but do not widen significantly. Cracking in the thin, tapered shotcrete over the anchor trench is moderate to severe (Fig. 4). Again, tapering of the shotcrete over the anchor trench is not recommended for future installations, instead the shotcrete should maintain a minimum thickness of 2 inches over the anchor trench.

Maintenance: Minimal maintenance requirements to date.

Test Section A-3 - Exposed 80-mil textured HDPE

Const. Cost: \$1.38/ft^2; L: 500 ft; Area: 15,000 ft^2

Condition: Very Good - After 5½ years of service (Fig. 5), the exposed HDPE liner is performing well, with only a few small tears over sharp subgrade rocks (Fig. 6).

Maintenance: Minimal maintenance required to date.

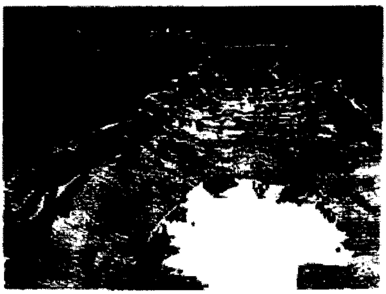

Fig. 5 - Overview of A-3

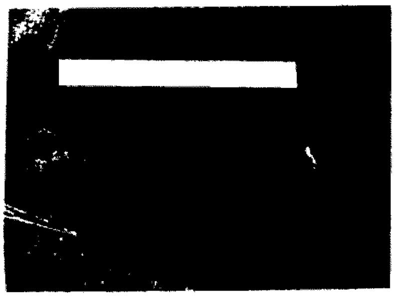

Fig. 6 - Tear in side wall above water surface

Test Section A-4 - Inverted PVC Geocomposite with geotextile cushion

Const. Cost = \$1.05/ft^2; L = 1,000 ft; A = 30,000 ft^2

Condition: Very Good - After 6 years (Fig. 7), the PVC is holding up well with no visible deterioration or stiffening, even where exposed. The geotextile cover is slowly weathering away (especially where unbonded at seams). Sediment (up to 1 foot deep) has collected in the invert providing additional UV protection. Some aquatic growth is impeding flow.

Maintenance: Minor maintenance required to date to repair damage (Fig. 8).

Fig. 7 - Overview of A-4

Fig. 8 - Tree fell onto liner during storm

Test Section A-5 - Exposed 45-mil CSPE with 16-ounce geotextile cushion

Const. Cost = \$1.11/ft^2; L = 500 ft; A = 15,000 ft^2

Condition: Very Good - After 6 years, the exposed CSPE geomembrane (Fig. 9) is holding up well. Standing water and a layer of sediment covers almost the entire invert, typically 0.5 to 1.0 foot deep. Some vegetation is growing but has little effect on flow to date. A couple of small tears have developed at the anchor trench (Fig. 10) and a sharp subgrade rock has punctured the liner at the waterline.

Maintenance: Minor maintenance required.

Fig. 9 - Overview of A-5 and A-6

Fig. 10 -Tears at anchor trench

Test Section A-6 - Exposed 36-mil CSPE geocomposite

Const. Cost = $\$1.03/ft^2$; L = 500 ft; A = 15,000 ft^2

Condition: Very Good - After 6 years, the exposed CSPE geomembrane (Fig. 9) is holding up well. The upstream transition between Test Sections 5 and 6 has a transverse adhesive-bonded seam which is working well. Backhoe operators have caused more damage to the exposed linings to date than any other element. A few small tears near the anchor trench need to be repaired.

Maintenance: Minor maintenance required to date.

Test Section A-7 - 40-mil PVC with 3-inch grout-filled mattress

Const. Cost = $\$2.36/ft^2$; L = 800 ft; A = 24,000 ft^2

Condition: Excellent - After 6½ years, the grout-filled mattress is in excellent condition, completely protecting the underlying PVC geomembrane. The mattress is fairly uniformly grouted in spite of the uneven rocky subgrade (Fig. 11). The outer fabric is beginning to deteriorate (Fig. 12), especially where subjected to abrasion. When the water is turned off, this test section holds water all winter, while the adjacent Test Section A-8 holds water for only a couple of weeks. This side-by-side comparison demonstrates the difference in seepage rates due to the geomembrane underliner.

Maintenance: Minor maintenance required to date.

Fig. 11 - Overview of A-7 and A-8

Fig. 12 - Mattress fabric is wearing away

Test Section A-8 - 3-inch grout-filled mattress

Const. Cost = $1.86/ft^2; L = 700 ft; A = 21,000 ft^2$

Condition: Excellent - After 6 years, the grout-filled mattress is in excellent condition with no freeze/thaw damage (Fig. 11). The first 200 feet with zippered seams has a much neater appearance than the second 500 feet with sewn seams. The grout-filled mattress is well tied-in to the bridge, with no gaps that would allow seepage. The outer fabric of the grout mattress is in good condition, with little deterioration, except for one location on the left bank where the geotextile has worn away, and several concrete "bricks" are missing.

Maintenance: Minor maintenance required to date.

Test Section A-9 - 60-mil VLDPE with geotextile cushion and 3-inch grout-filled mattress on side slopes only

Const. Cost = $1.79/ft^2; L = 1,000 ft; A = 30,000 ft^2$

Condition: Removed from study after 2 ½ years - Liner "whales" were restricting flow (Fig. 13). Attempts to deflate the "whales" with knife-cuts, and attempts to ballast with concrete blocks were largely unsuccessful as the "whales" tended re-appear elsewhere. Figure 14 shows contractor patching numerous holes, tears, and rips from sharp subgrade rocks. Eventually, the invert liner was removed with the grout-filled mattress left in place on the sideslopes. The cause of the "whales" in Test Sections A-9 and A-10 was never resolved. Volcanic gases are suspected to be the cause.

Fig. 13 - Liner "whale" impeding flow

Fig. 14- Patching of tears in geomembrane

Test Section A-10 - 60-mil HDPE with geotextile cushion and 3-inch grout-filled mattress on side slopes only

Const. Cost = \$1.79/ft^2; L = 1,000 ft; A = 30,000 ft^2

Condition: Removed from study after 2 ½ years - This test section experienced the same problems with liner "whales" as Test Section A-9. The exposed HDPE was removed in March 1995, and this test section was abandoned. The grout-filled mattress on the side-slopes will be left in place. In many locations, the imported sand bedding had completely washed away, indicating there may have been significant flow beneath the liner.

Test Section N-1 - SPUF with urethane protective coating
Test Section N-2 - SPUF with modified urethane protective coating

Const. Cost N-1 = \$4.33/ft^2; L = 300 ft; A = 18,000 ft^2

Const. Cost N-2 = \$3.92/ft^2; L = 300 ft; A = 18,000 ft^2

Condition: Partially failed - After 5 years, most of the invert foam has washed out of these test sections (Fig. 15). The washout initiated in the first few weeks of service just below the drop at the start of Test Section N-1 where loose sand and gravel deposits offered little uplift resistance to the buoyant foam (Fig. 16). The high velocities then undercut large, loose subgrade rocks, allowing more foam to break free. The failure then propagated downstream washing out the invert foam in Test Section N-2.

Fig. 15 - View after fifth year

Fig. 16 - View after first year

Test Section N-3 - Woven geotextile with spray-applied modified urethane coating

Test Section N-4 - Needle-punched geotextile with spray-applied modified urethane coating.

Const. Cost (both) = $\$2.64/ft^2$; L = 300 ft; A = 18,000 ft^2

Condition: Complete failure - On the first day of service, large sections of the geotextile liners washed out resulting in complete failure (Fig. 17 and 18).

Fig. 17 - View of foam anchoring system

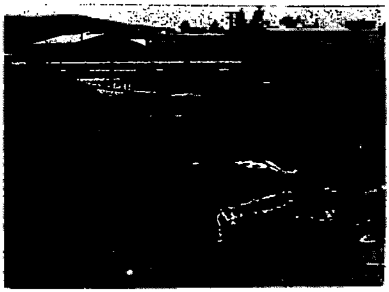

Fig. 18 - Lining floating downstream

Test Section N-6 through N-9 - General comments apply to all 3-inch shotcrete sections:

Condition: Excellent - After 6 years all the shotcrete is in excellent condition. No visible differences exist in the performance of the four shotcrete test sections. No freeze/thaw damage is evident. Small pools (Fig. 19) are present on all four test sections, even several weeks after water turn off, indicating low seepage rates. Contraction cracks on the side walls (Fig. 20) have developed every 100 to 200 feet. Crack width varies from hairline to 1/8-inch. The thickness of the shotcrete is highly variable (ranging from 1 to 6 inches thick) because of the uneven subgrade conditions, and normal problems with field installation quality control. Many large rocks (up to 1 foot in diameter) are collecting in the canal invert (perhaps rolled in by local youths). Vegetation is growing out of cracks in the shotcrete near the top of side slopes.

Table 2 - N-6 through N-9 Summary of Basic Data

Section	Description	Cost ($\$/ ft^2$)	Length (ft)	Area (ft^2)
N-6	shotcrete reinforced with steel fibers	$1.59	500	30,000
N-7	shotcrete reinforced with polypropylene fibers	$1.47	500	30,000
N-8	shotcrete reinforced with fibrillated polypropylene fibers	$1.47	500	30,000
N-9	unreinforced shotcrete	$1.33	500	30,000

Fig. 19 - Small pools holding water in winter

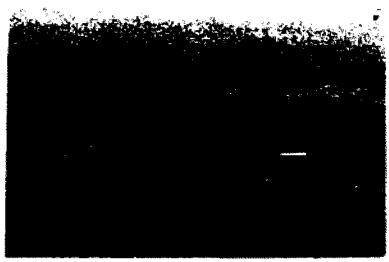

Fig. 20 - Contraction cracks in side walls

Test Section T-1 - Neoprene asphalt over an existing concrete flume

<u>Const. Cost</u> = $1.70/ft²; L = 175 ft; A = 1,575 ft²

<u>Condition</u>: Poor - After 4 years, the membrane is completely disbonded (due to high velocities) in the invert and has rolled up into the corners against the side walls (Fig. 21). Material on the vertical side walls has lots of small tears and pinholes (Fig. 22).

Fig. 21 - Material rolled up into corners

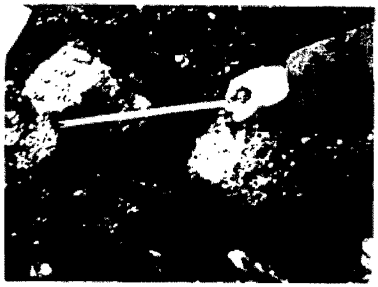

Fig. 22 - Small holes on side walls

Test Section T-2 - Neoprene asphalt over a sandblasted steel flume

Test Section T-3 - Neoprene asphalt over a broomed steel flume

<u>Const. Cost T-2</u> = $2.16/ft²; L = 465 ft; A = 7,870 ft²

<u>Const. Cost T-3</u> = $1.40/m²; L = 265 ft; A = 4,540 ft²

<u>Condition</u>: Very Good - After 3 to 4 years the membrane is well bonded to 99 percent of the steel flume (Fig. 23). No leakage is evident. Numerous blisters (Fig. 24) have developed where the membrane is poorly bonded to underlying old tar material.

Maintenance: Minor maintenance required to repair blisters.

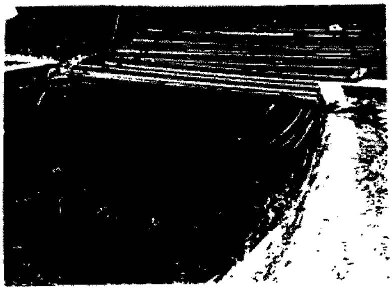

Fig. 23 - View of coated steel flume

Fig. 24 - Blisters formed on old tar

Test Section L-1 - Exposed 160-mil bituminous geomembrane

Const. Cost = $\$1.39/ft^2$; L = 2,400 ft; A = 70,000 ft^2

Condition: Very Good - After 4 years of service (Fig. 25), the geomembrane is in very good condition. Figure 26 shows a piece of new material on top of the 4-year-old material. The alligator cracking began to appear after about one year, but the material remains quite flexible.

Maintenance: Flood waters damaged the anchor berm, requiring minor repairs.

Fig. 25 - View of canal after 4 years

Fig. 26 - Comparison of liner (new versus old)

Test Section J-1. - Exposed 160-mil bituminous geomembrane

Const. Cost = $1.39/ft^2$; L = 900 ft; A = 7,215 ft^2

Condition: This new installation (only 6 months old) over fractured basalt (Fig. 27) has not yet gone through a full irrigation season (Fig. 28).

Maintenance: None to date.

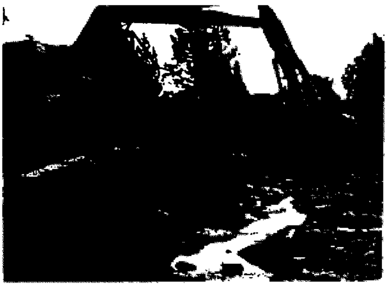

Fig. 27 - Trackhoe trying to excavate basalt

Fig. 28 - View of completed canal

CONCLUSIONS

How Much Do They Cost?

- This study has identified several effective lining technologies with construction costs between $1.05 to $2.36/ft^2$.

Exposed geomembrane	$1.05 - $1.79/ft^2$
Concrete alone	$1.33 - $1.86/ft^2$
Geomembrane with concrete cover	$1.79 - $2.36/ft^2$

Do They Work?

- Seepage reduction - Post-construction ponding tests showed that seepage had been reduced by 90 to 99 percent depending on the lining material. As expected, the 5-year ponding tests show some increase in seepage; however, seepage rates have still been reduced by 80 to 95 percent depending on the lining material. Geomembranes with concrete cover appear to provide the greatest long-term effectiveness.

- Maintenance - Test sections with exposed geomembranes are subject to mechanical damage and will probably require more maintenance than either concrete linings or geomembranes with concrete cover.

- Durability - Concrete linings have a proven life expectancy of 30 to 50 years. Since geomembranes are relatively new material, exposed geomembranes only have a proven life expectancy of about 20 years at this time.

- Future studies - The long-term effectiveness and durability of these 23 test sections will be addressed in a series of "Durability Reports." Life-cycle costs will include initial construction costs, maintenance costs, and design life (durability). Future ponding tests will be used in Cost/Benefit analysis to calculate the cost of conserved water ($/acre-foot).

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WATER RIGHTS AND WATER USE DATA HELP SET REGULATORY PRIORITIES IN A DEPLETING AQUIFER IN KANSAS

Thomas L. Huntzinger[1]

ABSTRACT

The High Plains aquifer provides the sole source of water supply for most of the western third of Kansas (figure 1). This unconfined or water table aquifer includes the Ogallala formation and hydraulically connected alluvial deposits. Regional withdrawals from this aquifer exceed recharge substantially in many areas. Water level declines have decreased the saturated thickness so that well capacities are limiting in many areas. Reporting annual water use is a statutory requirement in Kansas for all beneficial uses except domestic use. Additional data available as a condition of appropriated and vested water rights are: location of diversion, place of use, maximum annual quantity, maximum rate of diversion, and type of use. More than 95% of the water use is for irrigation and the arid climate results in very small amounts of precipitation. Comparisons of the reported water used, maximum authorized quantity, consumptive use of crops, and aquifer recharge provide basic information useful in setting regulatory priorities that will protect the public interest in addressing depletion of the water supply in this area.

STATE WATER PLANNING AND MANAGEMENT

Kansas Water Office

State agencies share in the responsibility for water management and planning in Kansas. The Kansas Water Office (KWO) is the state agency that provides the water planning functions for the state of Kansas through the development and updating of the State Water

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Plan. The Kansas Water Authority is a part of the Kansas Water Office whose 13 voting members represent the various water interests in the state that advises the Governor, legislature and the Kansas Water Office on water policy issues. In addition to the members of the water authority there are 10 non voting members that represent agencies or organizations within the state that administer some aspect of water resources or other interests that rely on water resources. The Kansas Water Authority also has a basin advisory committee of local citizens for each of the 12 major river basins within the state that advises the Kansas Water Authority and the Kansas Water Office on local interests and priorities within each river basin.

The Kansas Water Office has established objectives through the year 2010 that were developed through public forums and the Kansas Water Authority. These objectives include the evaluation of the condition of the water resources of the state and to establish a plan that decreases the water level decline rates in the Ogallala formation in western Kansas.

Division of Water Resources

The Division of Water Resources (DWR), Kansas Department of Agriculture, under the direction of the Chief Engineer appropriates water according to the prior appropriation doctrine and has the authority to regulate water use to protect water supplies in Kansas. The water appropriation program within the Division of Water Resources includes a water rights section in the state office that processes new applications for permits to use water, approves changes to permits to use water, and prepares certificates for water rights that are issued by the Chief Engineer. Kansas water law requires a permit for all beneficial use except domestic use. Water rights in Kansas have terms, conditions and limitations that include a file number, priority date, location of the diversion works, annual rate, annual quantity, a place of use, and a specific type of use. There are four field offices (fig. 1) in the state that assist the public with the water appropriation process. Each field office is managed by a water commissioner who is responsible for public assistance with the water appropriation process and has been delegated by the Chief Engineer with the authority to administer water rights according to priority in times of water shortage. Each permit to use water for beneficial use requires the user to report water use to the Division of Water Resources each year. Water use data is processed within the water rights section in the state office.

Groundwater Management Districts

There are five Groundwater Management Districts (GMD) located in the western and south central parts of Kansas (fig. 1) where ground water is the primary source of water supply. Groundwater management districts have a director and a staff that provides executive support to a board of directors elected by residents that own water rights within the district. The electorate in these districts is dominated by irrigation interests as most of the water rights are for irrigation. Membership on the board is based on a geographic distribution and by a member representing pubic water suppliers and in some districts the public at large or other specific water interests may be represented on the board. Groundwater management districts have the authority to levy a tax assessment on irrigated land and on water used. They establish water management policies and have specific delegated regulatory authority through the Chief Engineer to protect water supplies. Each groundwater management district develops a management plan and establishes regulations. The management plan must be reviewed by the Chief Engineer to ensure the plan does not conflict with state water management policies. Regulations must be reviewed and adopted by the Chief Engineer to ensure they are compatible with those of the state.

WATER USE REPORTING PROCESS

Water use report forms are sent to all of the approximately 31,000 water right holders in Kansas each January and are filled out by the water right holder and submitted to the Division of Water Resources by March 1 each year. The reports provide the annual quantity of water used, and in the case of irrigation, the amount of land irrigated, type of crops, the number of acres, and the type of irrigation system used. Municipalities (public water supply) report monthly quantities of raw water diverted from all points of diversion, water purchased, water sold, and water delivered to users. Fines are imposed by the Division of Water Resources for late reports which has resulted in more than a 90% response rate. Flow meters are required for all municipalities and for irrigation by the groundwater management districts or the Division of Water Resources in many parts of the state. A pumping rate and the hours the diversion works have operated for the year are used to compute water use in those areas where meters are not required.

Technical assistance and quality-control follow up increase the reliability and accuracy of the water use data. The primary responsibility for quality control of the data falls with the Division of Water Resources. However, the Kansas Water Office and the groundwater management districts assist the Division in these follow up activities. Follow up activities often require telephone calls, letters or a meeting with water users to clarify some aspects of their water use report. Division of Water Resources may use regulatory means if necessary to ensure accurate reports are filed. Water use data is entered into the water rights information system at the Division of Water Resources. Data in the water rights information system is protected by controlled access but is available to anyone upon request. The water use data set is provided each year to the Kansas Water Office and the groundwater management districts to use in their planning efforts and technical assistance programs. Water use data is analyzed by the Kansas Water Office to determine typical water use amounts and to identify water users with unusual or unreasonable water use that may be targeted for possible technical assistance.

OVERVIEW OF GROUNDWATER DECLINES IN THE HIGH PLAINS AQUIFER

Water development in the Ogallala formation and hydraulically connected alluvium that make up the High Plains aquifer in western Kansas has caused declines in water levels that exceed 100 feet since development started in the 1950s (fig. 2). Saturated thickness is less than 100 feet in much of the High Plains aquifer and exceeds 300 feet in many areas of southwestern Kansas (fig. 3).

WATER USE AND WATER RIGHT INFORMATION FOR WESTERN KANSAS GROUNDWATER MANAGEMENT DISTRICT NO. 1

Western Kansas Groundwater Management District No. 1, lies within the High Plains Aquifer, and has experienced water table declines that averaged about 35, feet ranging from less than 25 feet in some areas to more than 50 feet in most areas (fig. 4). Declines of 2 feet or less has occurred over most of Western Kansas GMD No. 1 during the 1998 irrigation season, however a decline of 4 to 6 feet has occurred in a few areas of the District during that time (fig. 5). The saturated thickness prior to development in Groundwater Management District No. 1 were between 50 and 100 feet except in southern Wallace county and central Scott County where saturated thickness exceeded 250 feet. The saturated thickness is now less than 200 feet in much of southern Wallace county and central Scott county and between 25 and 50 feet in most other areas (fig. 6). Saturated thicknesses between 25 and 50 feet are at the threshold for well yields sufficient for traditional irrigation practices and public water supplies. Continued water level declines will result in further expansion of the areas of marginal supply for irrigation and public water supply. There are wide areas that now have saturated thickness of less than 25 feet. It is anticipated that water supplies will become very limited if withdrawals continue at or near current rates.

General Depletion Rates

Groundwater supplies are being depleted as a result of long-term withdrawals that exceed recharge. The total amount of water in storage that is available for use by normal pumping methods is between about 6 and 8 million acre feet. Annual recharge rates indicate annual recharge to be 70,000 acre feet or less. During the 6-year period 1990-1995 reported annual water use ranged from 198,000 acre feet in 1993 to 389,100 acre feet in 1990 for an average of 292,800 acre feet. Assuming a sustained average withdrawal rate equal to that reported and an annual recharge rate of 70,000 acre feet the supply would be exhausted in 25 to 35 years. It is not likely that the withdrawals would continue at rates of the recent past but it is also possible that recharge rates may be less than the estimated 70,000 acre feet. However, the thickness of the aquifer and the withdrawal rates are not equally spaced throughout the area. Water supplies in some areas would be gone in much less than 25 years.

Climatic conditions during the period of most reliable water use data collection

Water use for irrigation is assumed to vary with the climatic conditions during the irrigation season. Soil moisture and precipitation during the growing season could affect the number of applications of irrigation water and the amount of municipal use. Water use information collected by the Division of Water Resources and maintained in the current data base began in 1988. However the reliability of the data was greatly improved after 1992 because of increased quality control on reporting and increased metering requirements. A comparison of the seasonal precipitation data for the years 1989 through 1997 was used to determine the year or years that would represent a typical climatic conditions and a typical water use year, a wetter than normal year and a drier than normal year. Data in table 1 shows 1993 was the year exceeding normal by the largest amount in Western Kansas Groundwater Management District No. 1 but this was not the case for most of western Kansas. However, 1996 exceeded the normal precipitation by the largest amount in most of western Kansas so was selected as representing a wet year. There were no representative dry years in the pèriod 1989 to 1997. The 1994 year was selected as a typical year as it was the most representative of normal precipitation for the years after 1992 .

Table 1

Comparison of average annual and seasonal precipitation with normal precipitation by year in Western Kansas Groundwater Management District No. 1

	Annual Precipitation			Seasonal Precipitation		
Year	Average	Normal	Pct.Diff.	Average	Normal	Pct.Diff.
1989	19.46	19.19	1.4	18.5	16.88	9.6
1990	20.85	19.19	8.7	16.82	16.88	-0.4
1991	19.93	19.19	3.9	16.84	16.88	-0.2
1992	23.1	19.19	20.4	18.12	16.88	7.3
1993	27.57	19.19	43.7	21.67	16.88	28.4
1994	19.37	19.19	0.9	16.06	16.88	-4.9
1995	20.09	19.19	4.7	19.19	16.88	13.7
1996	23.98	19.19	25	22.43	16.88	32.9
1997	23.81	19.19	24.1	20.67	16.88	22.5

1/ Average values from four long-term precipitation stations within Western Kansas Groundwater Management District No. 1
2/ Seasonal precipitation is for March - October.

Annual evapotranspiration for corn is estimated to be 28-30 inches in 1994

Annual evapotranspiration for corn is estimated to be 24-25 inches in 1996

Crop moisture demands represented by computed evapotranspiration of corn for climatic conditions during 1994 and 1996 are 28-30 inches and 24-25 inches respectively according to Kansas State University Extension Service information. The range in values is due to the different short season and long season varieties grown in the area. Comparing the seasonal precipitation with the computed evaoptransiration of corn shows that in the typical year 1994 that overall precipitation was within 9-14 inches of meeting crop demands, not considering the timing of needed moisture during the season. In a wet year represented by 1996, the precipitation was within 3-8 inches of meeting crop demands, not considering the timing of needed moisture during the season.

Decreasing pumping rates

Declining water tables and the accompanying decrease in saturated thickness have limited the pumping capacity of many wells. Pumping rates have decreased to the point that irrigation water use originally intended to sustain crops for optimum yields on original acreages are now controlled by pumping capacity of the wells in some areas. Pumping capacity tests, recorded in the Division of Water Resources data base, were conducted near the beginning of pumping when the water rights were developed, additional pump capacity tests have been conducted between 1990 and 1996 at many of these wells where meters were not required as part of a program to improve the accuracy of the water use reports. There were 320 wells that had pump capacity tests in the 1990's that also had a pump capacity test more than 10 years in the past. Most of the wells had tests between 10 and 20 years apart with some as long as 30 years. The pump capacity tests averaged 46% less over the 10-30 years ranging from 0 % to 94% less. It is apparent from a comparison of these pump capacity tests conducted more than a decade after the first test that well capacity is limiting water use. It is not known from this brief analysis how much of the decrease is attributed to well and pump deterioration and how much is attributed to decrease in aquifer yield or increased water use efficiency. However, it is reasonable to assume many owners would have repaired wells that had significant decreased pumping capacity if the aquifer was producing.

Water use characteristics

Compilations from the Division of Water Resources' water rights information system provides opportunities for comparisons that assist in water regulatory and water management decisions. Water appropriations processes are underway each day so the information in the water rights information system is continually changing. Therefore care must be taken in comparing compilations made at different times.

Selected information was compiled for Western Kansas Groundwater Management District No. 1 as shown in table 2. Water used for irrigation and some municipal purposes may vary from year to year with variations in climatic conditions. Therefore water appropriations provide a maximum authorized annual quantity on the water right that is considered reasonable to cover a dry year. It is assumed that reported water use will be less than this quantity most years. In an extremely dry year or a series of dry years during a drought, water use may approach the maximum amount authorized. Water use must remain equal to or less than the maximum quantity authorized to remain in compliance with the Kansas water appropriations act and not be subject to enforcement action by the Division of Water Resources. The maximum authorized quantity increased about 260 acre feet between 1994 and 1996 (from 753,730 acre feet to 753,988 acre feet) due to changes in water rights during this 2 year period.

More than 95% of the reported water use for both 1994 and 1996 was for irrigation. Reported water use varies from year to year in response to climatic and crop producer's management decisions. Reported water use for 1996, that represents a wet year, was less than 1994, even though the reported acreage was more. The irrigation water used per acre as reported in 1994 and 1996 was 1.2 and 1.0 acre-ft/acre respectively. Corn is the preferred irrigated crop in western Kansas. Therefore water use is commonly compared to the water demands of corn. In 1994 and 1996 the largest amount of water required by corn in addition to the seasonal precipitation was about 14 inches which is near the

Table 2

Water use summary for Western Kansas Groundwater Management District No. 2

	1994	1996
Net authorized quantity	753,730	753,988
Reported irrigation water use	281,921	252,931
Reported acres irrigated	237,532	245,309
Net authorized quantity for those not reporting or reporting no irrigation use	113,166	97,655
Reported non irrigation water use	7,101	6,649
Estimated domestic water use	488	484
Population	2,646	2,627

amount of 12-14 inches (1.0-1.2 acre-ft/ac) reported. This does not account for the timing of precipitation which may require more irrigation to cover short term dry spells within one season.

Climatic conditions during the years when reliable water use data are available were not representative of a dry year. Well capacity in many instances has decreased the ability to produce fully irrigated corn so more drought tolerant crops such as wheat and sorghum have replaced corn in many areas. During dry climatic conditions the reported water use would be expected to be greater but would probably not be close to the maximum authorized quantity in most cases. However those water rights for which no water use was reported may begin pumping and increase water use, realizing that many of these may be abandoned or not used even during a drought. If the authorized quantity for those water rights that had no reported water use were subtracted from the authorized quantity for all water rights the remaining potential use would be more than twice the reported amounts for 1994 and 1996. Water was sometimes appropriated for more than 2 acre-ft/acre but after 1978 it was appropriated reasonably consistently at 2 acre-ft/acre which is also nearly twice the rate of 1.0-1.2 reported in 1994 and 1996. The effect of the limitations on well capacity compared to management decisions to produce less water-demanding crops will not be possible until reliable water use data is obtained under dry climatic conditions.

Reported non irrigation use, which is primarily industrial and public supply, of about 7,100 acre-ft and estimated domestic water use of about 480 acre-ft is less than 3% of the reported water use. This is only about 7% of the authorized quantity for those water rights that did not report water use in 1994. However, sufficient well capacity may limit water supplies even for these uses in some areas.

CONCLUSIONS

Water rights and water use data are collected and maintained in the Division of Water Resources water rights information system. The Kansas Water Office, Division of Water Resources, and Groundwater Management Districts work together to support the planning, water management and regulatory functions in Kansas. Residents and irrigated agriculture in Western Kansas Groundwater Management District No. 1 rely on the High Plains aquifer for their sole water supply. Aquifer development since 1950 is depleting the aquifer. Water table declines are typically more than 50 feet. Saturated thicknesses are now between 25-50 feet in many areas. Saturated thicknesses of 25-50 feet or less are at the threshold of traditional irrigation practices.

The two years 1994 and 1996 represent a typical year and a wet year respectively– there were no dry years since 1992 when reliable data have been collected. More than 95% of the water used is for irrigation. In 1994 and 1996 the largest amount of water required by corn in addition to the seasonal precipitation was about 14 inches (1.2 acre-ft/acre) . This required amount is within the range reported of 1.0 to 1.2 acre-ft/acre. Well capacities in the past 10-20 years have decreased by more than 45% and this decrease is now limiting water use. Continued withdrawals at current rates would deplete the aquifer in 25-35 years.

Water management and regulatory strategies must address the short time frames of exhausting this sole source. Irrigation is the primary withdrawal from the aquifer and the remaining saturated thickness that would sustain traditional irrigation practices is in one or two locations of small areal extent. Water supplies for public supply and domestic uses, even though comparatively small, must be protected even when irrigation is no longer practical. Water use and water rights data collected and maintained by the Division of Water Resources provides essential information to monitor and manage this declining but essential resource. Comparisons of water use information and the characteristics of the aquifer provide insight into water management and regulatory priorities for the High Plains aquifer.

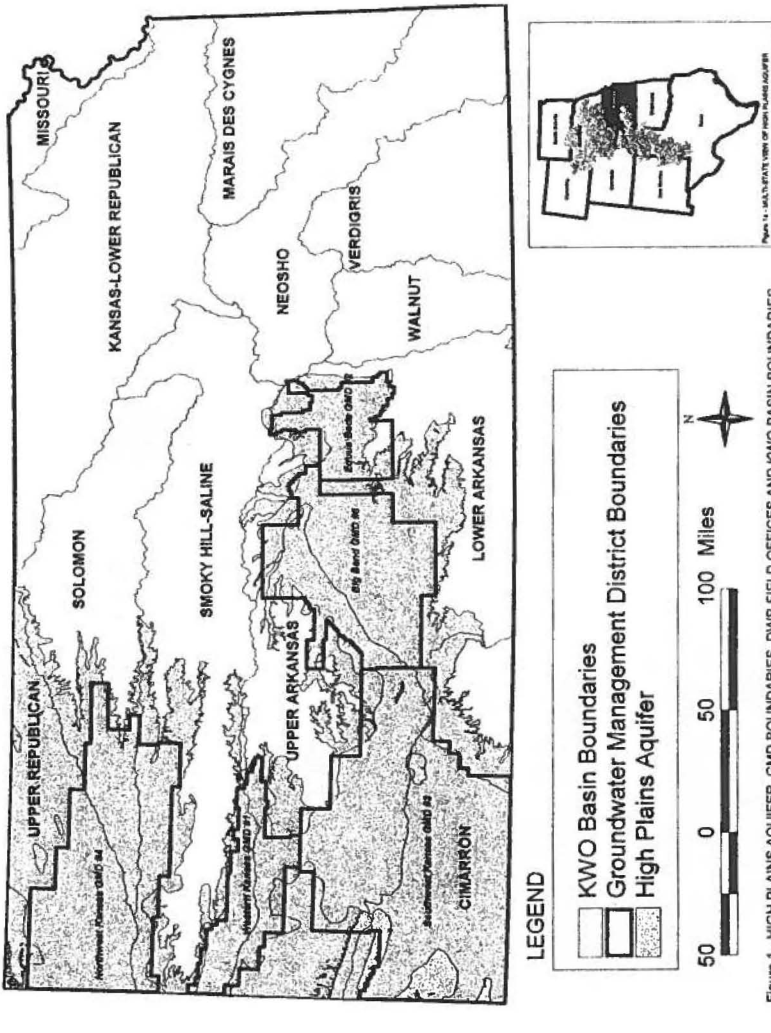

Figure 1 - HIGH PLAINS AQUIFER, GMD BOUNDARIES, DWR FIELD OFFICES AND KWO BASIN BOUNDARIES

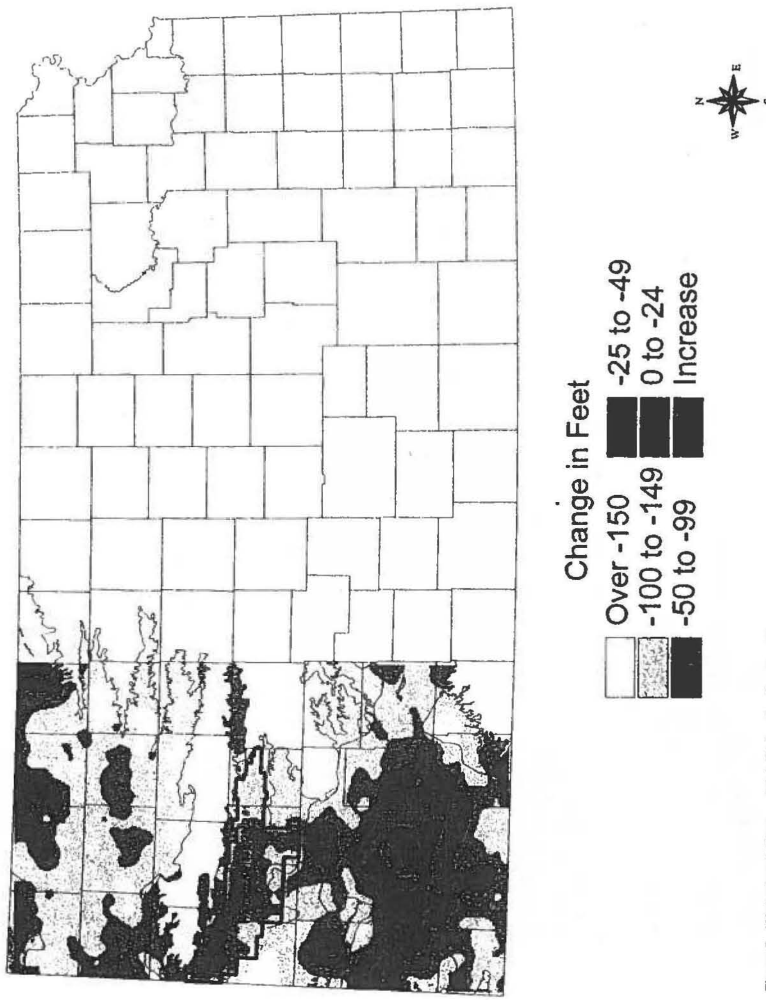

Figure 2 - Water Level Change, High Plains Aquifer, Pre-Development to 1999

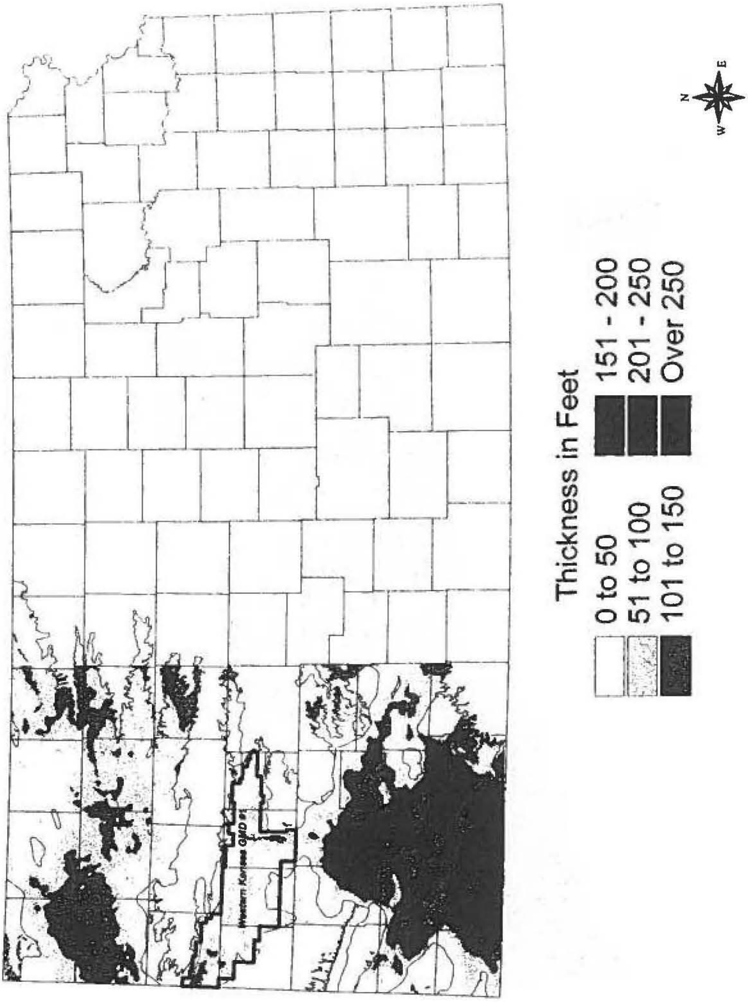

Figure 3 - Saturated Thickness, High Plains Aquifer 1999

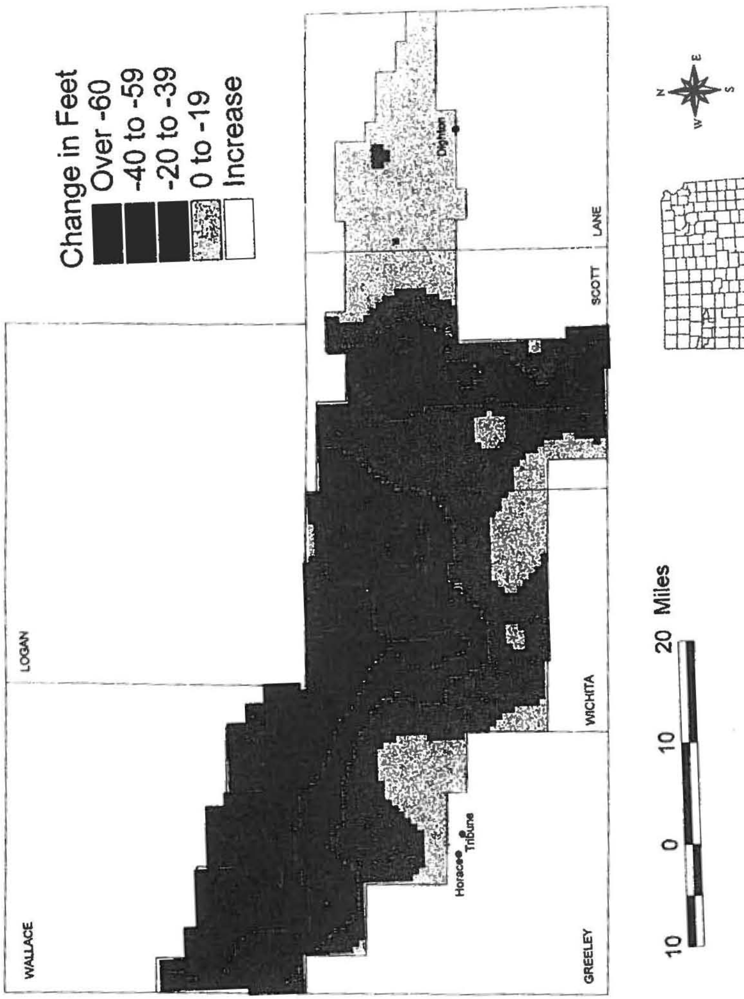

Figure 4 - Water Level Change, Western Kansas GMD #1, Pre-Development to 1999

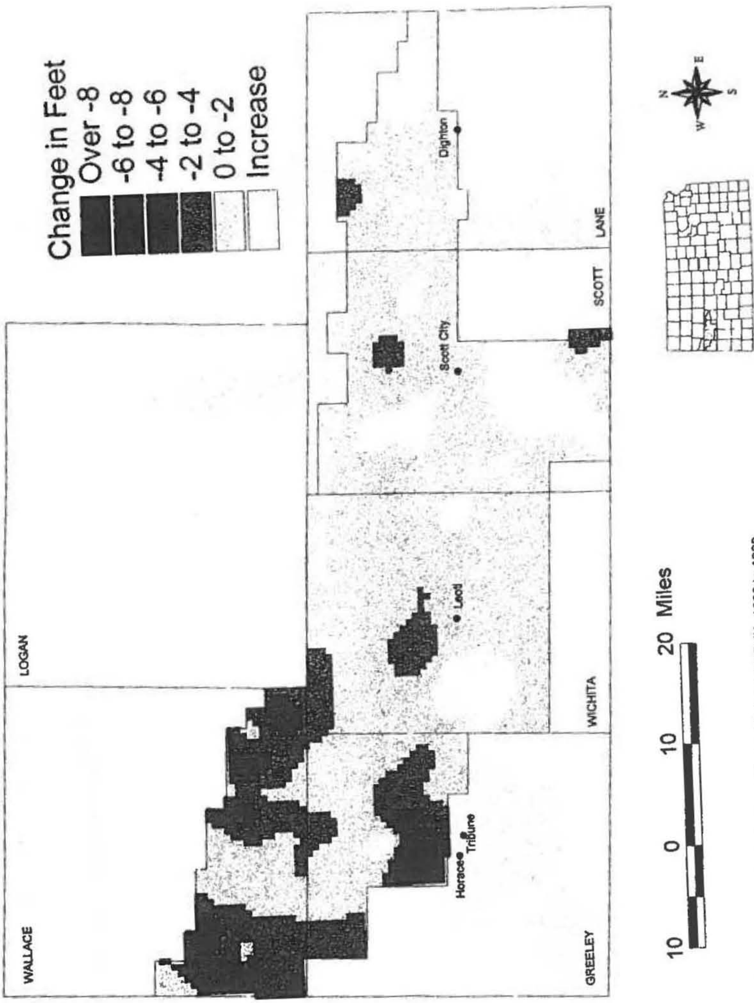

Figure 5 - Water Level Change, Western Kansas GMD #1, 1998 to 1999

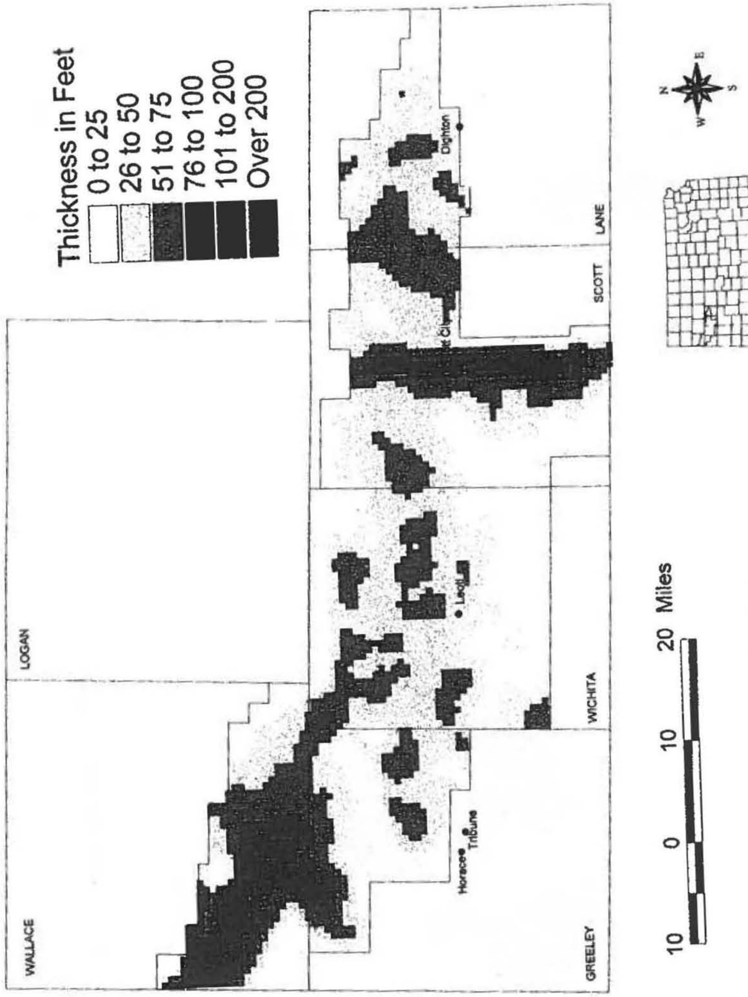

Figure 6 - Saturated Thickness, Western Kansas GMD #1, 1999

DOMESTIC USES OF IRRIGATION WATER AND ITS' IMPACT ON HUMAN AND LIVESTOCK HEALTH IN PAKISTAN

Waqar A. Jehangir, M. Mudasser and Nazim Ali[1]

ABSTRACT

The study documents different uses and users of irrigation water in Hakra 6-R canal command area in Haroonabad, Punjab, Pakistan. It reports the users' perceptions about quality of water for non-agricultural uses and issues related to other uses of irrigation water in the study area. In general, the household families use water from village water tank/ diggi. The water tank receives water from the canal on a weekly basis. The canal water allocation to the sample villages reveals that the average per capita daily water allowance varies between around 6-48 liters. Only 12% of the households have access to public water supply schemes. Regarding the average daily water use for various purposes by the households, the estimates show that water tank provides around 44% of daily water use. In total, the surface water sources account for 61% of the total water supplies (water tank, water supply scheme, and canal). The results show that current domestic use meets only 36% of the minimum daily water requirements of the household families. The estimates reveal that about 90 percent of the households were suffering from water-borne diseases. About 74 percent households reported use of surface water (Water tank, Supply scheme etc.) through applying simple cloth filter. The study proposes that further research should be conducted to document the economics of non-irrigation uses of irrigation water and water quality & its impact on human and livestock health.

INTRODUCTION

In Pakistan where 69 percent of its population lives in the rural areas (GOP, 1995). The irrigation water supplies to rural areas have multiple roles to play for the sustainable development, by their contribution in the agricultural and non-agricultural uses. A large segment of rural population in the Punjab is deprived of public sector drinking water supply and sanitation facilities. Instead of the best efforts of the Punjab government to the rural water supply and the drainage sector,

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the situation remains very precarious. Presently about 44 percent of the rural population in the Punjab has access to clean drinking water. Rural population served with the sanitation facilities in the Punjab is only 21 percent (Jatala, 1995).

Through the review of literature, we found that most of the studies in Pakistan, conducted in the past revolved around the agricultural uses of the irrigation water and non of the study in Pakistan provides us any pragmatic estimates on the contribution of irrigation water to the non agricultural uses in terms of provision/use of water for households, livestock, wild life and aquaculture Altaf et al (1989), Altaf et al (1993), Islam et al (1992) Rahman et al (1988). Thus, in the absence of such estimates, these additional benefits are likely to be ignored when the irrigation management practices like warabandi schedule/canal closure etc. are modified to maximize the agricultural output per unit of water. For example, seasonal/rotational water supplies in distributaries/minors will result in their closure for long period and will deprive populations of water supplies for other needs. The closure of canal, with or without ground water supplies pumping (for meeting irrigation demands), will result in lowering the water tables and will dry-up drinking water well in sweet water zones and will lead to the intrusion of saline/marginal water in the brackish water zones.

Thus, while representing the impact of irrigation supplies on the rural productivity, it is very critical to take in to account the distinction between the agricultural and non agricultural uses of irrigation water, other wise the analysis will be seriously flawed and will lead to under estimation of the benefits accruing through the modified irrigation management practices. Only few research studies have been conducted in Pakistan regarding the rural water supplies and mainly they were focused on the rural water supply policies or evaluation of the rural water supply program in Punjab (Altaf et. al 1993, World Bank Water Demand Research Team 1993 and Rehman et al, 1988). Similar investigations have also been conducted in India (Griffin et al, 1995, Singh et al. 1993 and Bhatia, 1992). Non of these inquiries talked about the non agricultural uses of irrigation water, especially in the rural areas which falls in the sweet/ brackish water zones, where the irrigation supplies serves as the major source of water supply for household uses (micro enterprises).

In Pakistani rural conditions the problems in brackish water zones are different from the sweet water zones. In the brackish water zone, the people are bound to use the irrigation water for their domestic uses. Irrigation water is weekly added to the unpaved open community pools and then the whole village community directly takes water from these pools for their household consumption without any formal filtration or treatment. Further more the water of these pools get contamination and is being polluted when animals of rural household are taken to these community pools, as these pools also serve as the source of drinking water for the domestic animals.

In the sweet water zone most of the times the rural communities use the ground water for the household consumption. Due to the non-availability of proper drainage facilities, the people construct the soaking pits 25-30 feet deep and connect the septic tanks of their toilets with those pits. Usually an electric motor pump or a hand pump is also installed in the vicinity. This leads to serious health hazard, if the water from the soaking pit mixes with the layer of fresh ground water. In some of the areas where the public water supply facility has been provided this problem is more severe as the drainage conditions in those rural areas are much worse as compare to the others. It leads to the frequent incidence of water related diseases. It is estimated that 30 percent of all reported cases of illness and 40 percent of all deaths in Pakistan are attributable to water borne diseases and the main sufferers are the rural inhabitants (GOP, 1988). Further more enormous amount of work hours due to such poor conditions and constitute a significant economic loss to the rural households.

The present study documents the spatial comparison of non agricultural uses of irrigation water by different users located in the Head, Middle and Tail reaches of Hakra 6-R Distributary in Tehsil Haroonabad, Punjab, Pakistan. The provision of water in the H-6-R Distributary depends upon a number of upstream irrigation Link Canals and Barrages. From the left bank of the Sulemanki Headwork, Eastern Sadiqia canal originates and after covering a distance of about 46 mile (74 kilometers) split into Hakra Branch canal, Malik Branch canal and Sirajwah Distributary. From the main Hakra canal, two distributaries originate near Head Mianwala Bangla, i.e. Hakra 2-L and Hakra 6-R Distributary while main Hakra canal continues its journey towards the tail reaches. The H-6-R Distributary covers a gross command area and a canal command area of about 51976-hectare and 42538 hectare, respectively. The main H-6-R Distributary is about 45 kilometers long and has 283 outlets. The authorized discharge of the H-6-R Distributary is 16.65 M^3 in Kharif season and 15.5 M^3 in the Rabi season. Out of the total (94) villages in H-6-R twenty-four villages (i.e. eight villages from each head, middle and tail reach of 6-R Distributary) were selected for the current study. The study investigates different sources of water, their quality as perceived by the users and the impacts of alternative sources of water in the saline areas on human and livestock health.

OBJECTIVES

The objectives of the study are to:

1) Document users' perceptions about quality of water for non agricultural uses; and

2) Determine the incidence of water borne diseases and their impacts on human and livestock population in the study area.

DATA COLLECTION AND ANALYSIS

A multistage stratified random sampling technique was used to select the sample from the study area. At the first stage H-6-R was stratified into Head, Middle, and Tail reach on the spatial basis. At the second stage, 24 villages were randomly selected from all of the three. Reaches (Figure 1). At the third stage a sample of 120 households in each reach was selected. Thus the total sample size was 360 respondents. The data were collected from both the male and female head of the households, using a structured questionnaire that was pre-tested twice in the field. The data were entered in the field in a spreadsheet format using Q-Pro software. After data entry the data processing took significant amount of time and efforts. The Statistical Package for Social Scientists (SPSS) was used to analyze the data. Simple frequency distribution and cross tabulation was used for data analysis.

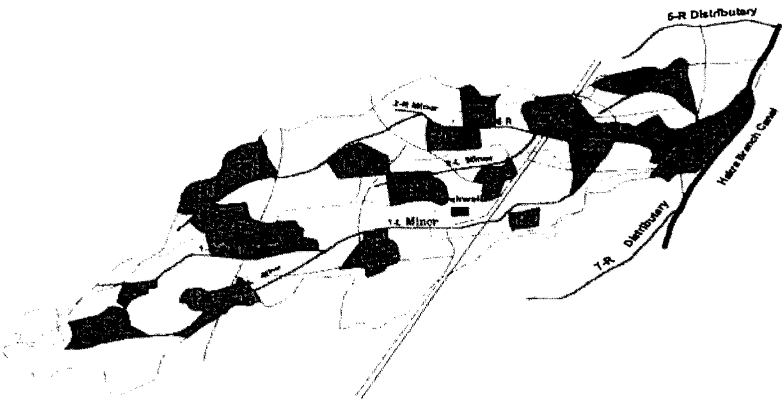

Figure 1. Location of Sample Villages in Hakra 6-R Distributary in Haroonabad, Punjab, Pakistan

RESULTS AND DISCUSSION

Quality of Water

About 58 percent of the respondents regarded the quality of groundwater better as compared to that of the surface water. Almost 62 percent of the respondents (who used groundwater) and almost half of the users of canal water and supply schemes were also unaware of the type of contamination. More than 55 percent respondents believed that dust particles and a mixture of dust, salt, sanitation wastage, insects, biological life, etc contaminated the surface water. About 28 percent of the respondents opined that the groundwater was contaminated with salts.

Impact of Non-Irrigation Uses on Health

Water Borne Diseases in the Sample Households : The estimates revealed that 32 percent of patients suffered from malaria as compared to other water-borne diseases. The other most important water-borne diseases in the study sample were Dysentery (17%), Skin diseases (13%), Typhoid fever (11%), Cholera (9%) and Diarrhea (8%). About 12% of the respondents reported the incidence of other three diseases i.e. Jaundice, Kidney stone and Cancer. Higher incidence of Diarrhea was recorded in the Tail and the Middle regions (12% and 9 % respectively) as compared to Head region (2.5%). The respondents infected by Cholera ranged from 9-10% in all the three regions.

Perceived Impact of Domestic Water Supply on Human Health : About 59 % of the users perceived surface water as main cause for cholera, jaundice, kidney stone, malaria, typhoid, and skin diseases. On the other hand, only one respondent regarded groundwater as the main cause for diarrhea. Around 75% were consuming groundwater for drinking purposes, which also points to their perception that the surface water caused diseases more than the groundwater.

Water Associated Diseases and Expenditures Incurred by the Households: The estimates reveal that about 90 percent of the households were suffering from water-associated diseases. Total financial loss (amount spent on treatment plus wages lost) was estimated to be Rs.122949, Rs 165938 and 236666 in the Head, Middle, and Tail reaches, respectively. Average treatment cost per household was worked out to be Rs.1149, Rs. 1536 and Rs. 2132 in Head, Middle and Tail reaches, respectively during 1997.

Diseases and the Source of Treatment: Different types of treatment are used for the cure of various diseases i.e., traditional treatment from compounder, quack, and doctor depending upon income of the household, distance of doctor's clinic, acuteness of the disease, and availability of required medicines. Majority of the people got treatment from doctors for all the water borne diseases except malaria.

Only 37% of the sample households reported use of simple techniques such as boiling, chemicals (Alum or $KMnO4$) and clothe filtering. Like Harnmeijer 1993, it was noted that frequency of using remedial measures particularly boiling of water and use of chemicals (mentioned above) was higher among educated households than those with less education. About 74 percent households reported use of surface water (Water tank, Supply scheme etc.) through applying only plain cloth filtering to avoid dust/silt, tadpoles. Water tank is the major source that needs some type of treatment, as it has more chances of getting polluted by dust/silt etc.

Impact on Livestock Health

About 60 percent of the livestock population held with the sample households is affected from different water associated disease like diarrhea, dysentery and foot & mouth disease etc. It is estimated that 48 percent of cattle, 70 percent of buffalo and 57 percent of goat population were affected from water associated diseases in 1997.

Impact on Environment

Almost 89 percent of the respondents perceived wastewater as the cause of problems for them. The percentage increases from Head to Tail region because Head and Middle reach farmers have comparatively better self made sewerage system as compared to the Tail reach villagers.

SUMMARY AND CONCLUSIONS

- Majority of the users did not know about the source of contamination in their water supply. Those who knew perceived that much of the contamination in the surface and groundwater was either local by origin or a combination of both local and remote pollutants.

- Many users (45%-88%) did not know about the type of contaminants. Those who knew opined that the surface water contained dust, animal and human excreta, sanitation water, insects and biological life. The main pollutants in the groundwater were salts.

- Frequency of water borne diseases was high (75%) during summer seasons as compared to the other seasons.

- Malaria, Dysentery, Skin problems and Typhoid fever are the most prevalent diseases of the whole area, incidence of that was comparatively higher in the tail region of the Distributary.

- Percentage of male adults and children infected by water related diseases were higher as compared to females.

- Around one-third of the sample households reported the adoption of remedial measures.

- Frequency of using remedial measures, particularly use of cloth filters and Alum salt etc. was higher among educated households than less educated.

- About 60% of the livestock population owned by sample households were affected by water borne diseases during 1997.

AREAS FOR FUTURE RESEARCH

Economics of Non Irrigational Uses of Irrigation Water

The current study has documented the users, the uses, the sources and the perceived quality of irrigation water being used for non-agricultural uses and its impact on human and livestock health. The in-depth analysis needs to be conducted to estimate the economic benefits of the improved water supply schemes in the area.

Water Quality and Irrigation

Poor quality irrigation water impacts on both human health and crop yields in irrigation systems. The agricultural activities in these systems also impact on down stream water users. There is need to conduct research on groundwater quality to develop guidelines for the use of low quality irrigation water to reduce the salinity problem for sustainable agriculture.

Control of Vector Born Diseases

The study reported the household's perception about the incidence of water borne diseases. A study needs to be conducted to test the statistical relationship between malaria, diarrheal diseases and the use of irrigation water.

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AN ENVIRONMENTAL SOLUTION FOR INDUSTRIAL EFFLUENT REUSE

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ABSTRACT

The Snowflake Mill is located in a rural setting in Arizona. Through its paper-making process, the mill produces approximately 14 million gallons of effluent each day. Historically, this effluent had been discharged to a natural body of water called "Dry Lake". In 1992, however, the U.S. Environmental Protection Agency (EPA) issued a consent decree which required the effluent either to be treated or cease discharging into Dry Lake. In the absence of complying with these requirements, EPA would seek the suspension of the mill's operations. After carefully evaluating various alternatives, the solids recovery system and biomass irrigation approach was chosen to be implemented for the complete elimination of the discharge to Dry Lake.

Entellus, Inc. was retained by Abitibi Consolidated to provide planning, design and construction management services for the biomass irrigation project. The key components of the project included a 3,500- acre biomass plantation, two 30- and 36-inch diameter pipelines with lengths totaling 22,000 feet, approximately 14 miles of unlined earthen ditches, and a 260-acre impoundment formed by a 6,000-foot long earthen dam. The construction of the entire biomass irrigation project was completed at the end of 1996.

The approach of biomass irrigation for effluent reuse has been proved to be extremely successful. It eliminated the need for advanced treatment and pumping facilities and in turn saved $50 million in capital investment and $10 million in annual operation and maintenance costs. In addition to the socio-economic benefits, this approach offers an opportunity to conserve a precious water resource. The project has become an environmental showplace in which the State of Arizona and Abitibi Consolidated can take pride.

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INTRODUCTION

Abitibi Consolidated Inc. is one of the world's largest paper companies based in Montreal, Canada, with paper mills, sawmills and sales offices throughout the world. Their Snowflake Mill, which is the site of the improvements described below, is the second largest producer of recycled paper products in the United States.

Project Location

The Snowflake Mill is located in a rural setting approximately 17 miles west of Snowflake, Arizona abutting the southern edge of the Colorado Plateau at an elevation of 6200 feet. As shown in Figure 1, the mill facility encompasses a total of approximately 22 square miles (14,080 acres) of land. The terrain around the mill is relatively flat with occasional slightly rolling hills. The vegetation is characterized by grassy plains intermixed with stands of Pinon and Juniper trees.

The mean annual precipitation in this area is around 12 inches, falling normally in two distinct seasons. One season, primarily resulting from local convective storms, lasts from July to mid-September; the other season, mainly caused by frontal storms, extends from December through March. Winter precipitation often occurs in the form of snow.

Average summer temperatures in this area range from the high 50s in the early morning to the high 80s in the afternoon. Daily temperatures during the winter months range from the low 20s to the high 40s.

Need for the Project

The Snowflake Mill started its operation in late 1961. Through its paper-making process, the mill produces approximately 14 million gallons of effluent each day, which is equivalent to 22 cubic feet per second (cfs). The effluent has a high concentration of residual paper solids. However, it does not contain extraordinary constituents that are harmful to human or livestock. The sodium concentration in the effluent is relatively high, ranging from 400 to 500 parts per million (ppm). Furthermore, as a result of the de-inking process for newspaper recycling, the color of effluent appears to be grayish.

Historically, this effluent had been discharged to a natural body of water called "Dry Lake," which is situated on the west side of State Route 377, approximately 10 miles north to the mill. However, in 1990, waters in Dry Lake were re-classified and brought under the jurisdiction of the U.S. Environmental Protection Agency (EPA). In 1992, EPA issued a consent decree that called for the treatment of effluent that would meet a standard similar to drinking water standards, or

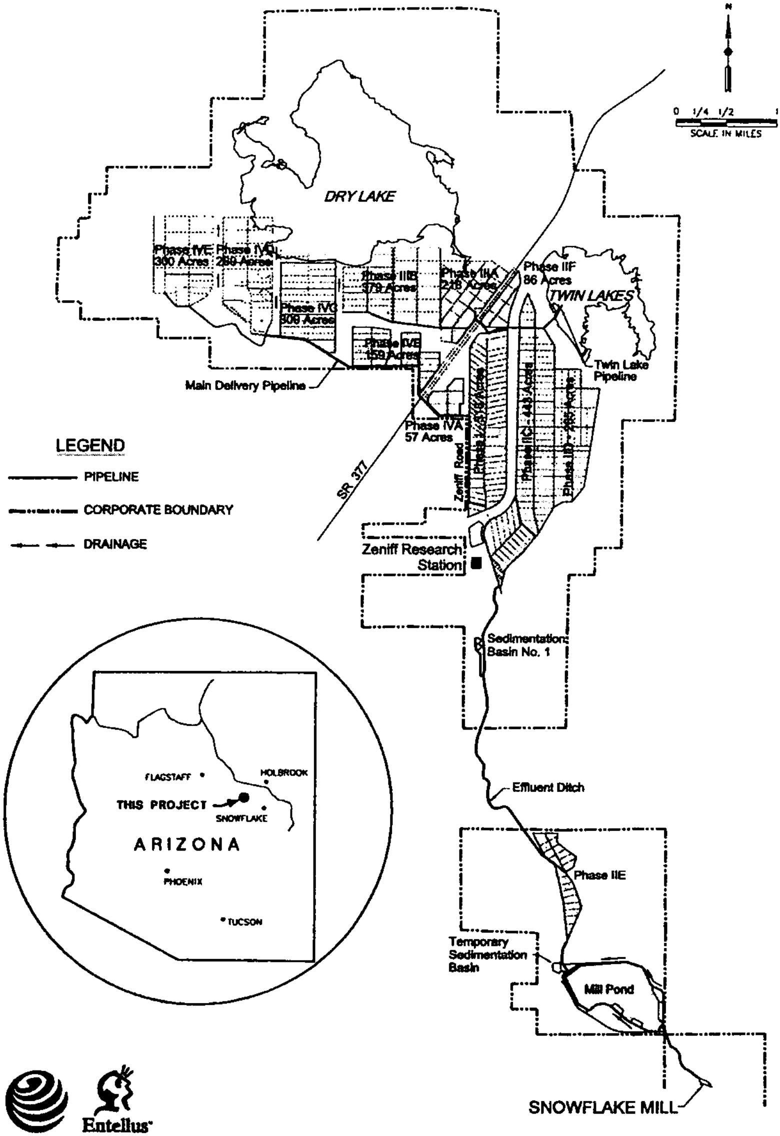

FIGURE 1 - ABITIBI CONSOLIDATED BIOMASS PLANTATION

complete elimination of the discharge into Dry Lake. Final date for compliance with the decree was set to be January 1, 1997. In the absence of complying improvements, EPA would seek the suspension of Snowflake Mill's operations. In response to the decree, Abitibi Consolidated launched a comprehensive program to seek sound solutions to these environmental issues.

PROJECT FORMULATION

Alternatives Considered

Numerous ideas were generated during the extensive study. After a screening process was applied to eliminate the less desirable ones, the following three alternatives received more detailed analysis and evaluation:

Alternative 1: Construction of a lined impoundment to dispose the effluent through natural evaporation process.

Alternative 2: Construction of a primary, secondary and tertiary treatment system to improve the effluent quality to meet the required standards specified in the decree.

Alternative 3: Construction of a solids recovery system in concert with effluent reuse through irrigation.

Under Alternative 1, an impoundment capable of storing the 14 million gallons per day of effluent would require the construction of a dam 4.3 miles long and up to 110 feet in height, and a surface area of 2,600 acres to dispose the effluent through evaporation process. The total cost for this alternative was estimated to be $187 million. As for Alternative 2, the capital cost was estimated to be $69 million, with an estimated annual operation and maintenance cost of $13 million. Alternative 3 was selected because it was proved to be the most cost-effective approach to solve these environmental needs. The total construction cost for the solids recovery system and the biomass irrigation facilities was estimated to be $21 million. Moreover, this approach provides the greatest amount of flexibility, creativity, and innovation in mitigating negative environmental impacts.

Project Implementation

The project first installed a solids recovery system to improve the effluent quality by removing the high residual paper solids thus making it more suitable for irrigation use. The solids recovery system consists of two flocculation tanks with dissolved air floatation devices, two solids collection tanks, and three belt presses for solids thickening and dewatering. Solids removed from the effluent are used as compost or landfill covering material.

After the solids recovery system was completed in 1992, Abitibi Consolidated retained Entellus, Inc. to perform the planning, design and construction management services for the biomass irrigation project.

"Biomass" is a general term used for describing the biological mass such as crops, plants and trees that collectively consume the effluent. Key components of the biomass irrigation project are:

- The 3,500-acre biomass plantation
- The conveyance system for irrigation
- The storage facilities

The construction of the entire biomass irrigation project was completed at the end of 1996.

THE BIOMASS IRRIGATION PROJECT

The Biomass Plantation

Farm Layout : The biomass plantation consists of approximately 3,500 acres of farm fields. The on-farm layouts were developed based on the level border irrigation method. The reason for choosing level border irrigation method was two-fold. First of all, this method calls for flooding of flat fields that fits the criteria of zero discharge from the biomass plantation. Secondly, the natural terrain of the plantation site is relatively flat and hence the development cost would not be too expensive. The size of each field ranges from six to nine acres.

Turnouts : Water is fed to the fields through a series of 15-inch diameter pipe turnouts. A galvanized toggle gate (which is a form of slide gate) is attached to the head of each turnout for flow control and regulation. The turnout is made of high density polyethylene (HDPE) pipe due to its low installation cost and the ability of endurance to ultra-violet exposure. Alfalfa valves were not used due to high concentration of paper solids in the effluent.

Land Grading : The native soil at the plantation is high in clay content. Without some positive drainage, the floor of the field would result in uneven moisture content, especially near the turnout locations along the irrigation ditches. Therefore, each field was designed with a mild slope of 0.0007 ft/ft. This amount of slope was determined to be optimal for providing enough drainage while minimizing areas of over-irrigation that would negatively impact crop production. During the construction phase, laser-controlled scrapers were used for precise final finishing.

Cropping Pattern : The two main crops grown at the biomass plantation are alfalfa and sordan. Now, the yields of these crops are approaching one and one-half that of naturally grown crops in the same region. In addition, an experimental area of 300 acres within the plantation is designated for research on optimizing growth for various species of trees. Under a study grant, the Northern Arizona University School of Forestry is currently assisting Abitibi Consolidated personnel in monitoring this research program.

The Conveyance System

One of the greatest challenges of this project was to design a gravity conveyance system that would avoid the need for large volume pumping facilities and thereby reducing the $3 million in anticipated annual operation and maintenance costs. This was accomplished by using a combination of pipeline and ditch systems to deliver the effluent from the solids recovery facilities at the mill to various areas in the plantation.

Pipelines : Two large pipelines were installed on the project: the main delivery line which consists of approximately 15,000 linear feet of 30- and 36-inch diameter pipe; and the Twin Lake pipeline which includes approximately 7,000 linear feet of 30-inch diameter pipe. Both pipelines are subject to approximately 25 feet of water pressure. After researching various alternatives for low-head pressure pipe materials, Entellus selected single-wall HDPE pipe with thermal-welded joints. Although this type of pipe is typically used in the mining industry for conveying slurry tailings, it has demonstrated a successful application for this project. The use of this material resulted in a savings of approximately $350,000 over other conventional piping materials.

In using this type of pipe with concrete structures, minor modifications to the structure walls were required to ensure that the dissimilar coefficients of expansion between concrete and the HDPE material would not create undesirable leaks. In addition, ordinary irrigation sluice gates were found to be inadequate for handling pressures in the piping system. Through value engineering, stainless steel knife gates on the outlet end of the pipelines were used in lieu of the more expensive high-head sluice gates, saving approximately $50,000.

Earthen Ditches : One of the primary criteria of this project was to meet the compliance requirements with the least amount of capital improvement cost. Therefore, the approach for irrigation system design considered under this project was somewhat different from conventional irrigation practice. In a semiarid region, the width of an irrigation ditch is often kept at a minimum in order to minimize water loses through evaporation and seepage. In this project, however, ditch configuration in terms of saving water was not a primary concern.

Approximately 14 miles of unlined earthen ditches were constructed in the plantation. Each ditch was sized for a capacity of 22 cfs. The typical section of ditches consists of a trapezoidal shape, with 4-foot bottom width and 2:1 side slopes. The depth of the ditches varies between three and four feet. Service roads are provided along both sides of ditches. The longitudinal slope of the ditch is maintained at 0.001 ft/ft to minimize erosion.

Concrete checks were installed in the ditches for placing redwood boards to raise the water surface during irrigation. At some locations, these concrete checks also serve as drop structures. Division boxes were constructed at key locations for water distribution and regulation. Aluminum slide gates, which is inert to the effluent water quality characteristics, were used with the division boxes.
Inverted siphons were constructed where ditches cross the corridor of power transmission lines or natural washes. The HDPE pipe with water tight joints was used for the construction of inverted siphons. Trash racks were placed at the entrance of inverted siphons to protect the facilities from clogging.

Flow Measurement : A Parshall flume is located at the outlet of the solids recovery facility to measure the effluent from the mill. This flow measuring device was installed when the mill started its operation in 1961. With the implementation of this biomass irrigation project, two more metering stations were installed. These new metering stations are remotely located and operate strictly on solar power. One station is located at the outlet of Mill Pond, and the other at the inlet of Twin Lake. The two new metering stations use doppler-type flow meters to determine flow rates. Each station consists of two 42-inch diameter HDPE pipes, with metering devices clamped on the monotube HDPE pipe wall. The capacity of each metering station is up to 70 cfs.

Storage Facilities

The project site is situated on a plateau at an elevation of 6200 feet. Crops cannot grow during the severe weather in winter. In order to meet the commitment of zero discharge to Dry Lake, the mill effluent must be stored in impoundments outside the biomass plantation throughout the entire winter season. Based on a water balance study, the required storage volume was estimated to be approximately 5,000 acre-feet. The existing Twin Lake (which was built in 1984 at the upstream end of Dry Lake) could provide 2,400 acre-feet of storage. Thus, an additional 2,600 acre-feet of storage impoundment was needed. As a result, the Mill Pond was designed and constructed as a part of the biomass irrigation project to provide sufficient storage in winter seasons.

Mill Pond : The Mill Pond is located immediately northwest of the mill. The impoundment was formed by constructing a 6,000 feet earthen dam on the upstream end of the effluent ditch. There are two sediment basins flanked along each side of the upstream end of the pond. The maximum embankment section has a height of 37 feet. The downstream slope of the embankment is 2.5(H) to 1(V), while the upstream slope is 3(H) to 1(V). With a freeboard of 6 feet, the maximum water depth in the pond is 31 feet. The surface area of the pond is approximately 260 acres. The outlet structure is located at the northwest corner of the pond where the original effluent ditch intersects the embankment. The outlet structure is composed of two 30-inch diameter reinforced concrete pipe openings, regulated by an aluminum sluice gate at the inlet of each pipe.

Pond Lining : The embankment is classified as a jurisdictional dam that is regulated by the Dam Safety Section of the Arizona Department of Water Resources (ADWR). However, as the facility is used for the storage of industrial effluent, the impoundment is also under the jurisdiction of the Arizona Department of Environmental Quality (ADEQ). In order to meet ADEQ's aquifer protection criteria, lining was provided for the impoundment to ensure a permeability not greater than 1×10^{-7} cm/sec. Several alternatives were considered and the most economical solution was to use native clay as the lining material. During the construction phase, several testing pads were prepared within the impoundment site where native clay materials had been selected, blended, pre-moistened, and compacted to 98% of the optimum density. These pads were tested and the results were satisfactory. Based on the experience from these testing pads, a specific process was developed to blend the existing native clays with proper compaction to form a 260-acre soil liner which met the permeability requirements. The clay liner was built in level tiers to prevent dessication when the pond is empty.

Pond Bypass : An earthen bypass ditch was constructed around the north side of the pond to provide complete bypass capability for the mill effluent should the pond need to be closed for maintenance or repair. This bypass ditch also serves as the outlet channel of the emergency spillway, which is located at the northeast corner of the pond. The ditch consists of a trapezoidal cross-section with a bottom width of four feet and 2.5(H) to 1(V) side slopes. Drop structures were installed along the ditch for erosion protection.

CONCLUSION

The approach of biomass irrigation was effectively applied as an innovative solution for industrial effluent reuse at the Snowflake Mill in Arizona. The project, including the Mill Pond, was constructed at a cost slightly over $20 million. It eliminated the need for advanced treatment and pumping facilities and in turn saved approximately $50 million in initial capital investment. In addition, the project requires zero annual operation and maintenance costs due to the revenues received from crop production. It provides an additional savings of $10 million over the next best alternative each year.

The Snowflake Mill has significant economic importance to rural Navajo County and the State of Arizona. It is the single largest employer in Navajo County. Over 1,000 persons are directly or indirectly employed as a result of the mill's operations. With the great cost savings on effluent disposal, the mill is able to continue its operation in this competitive market and provide vital input to the regional economy.

In addition to the socio-economic benefits, this effluent reuse approach offers an opportunity to conserve the scarce water resources - a precious commodity in the desert southwest. With the successful conversion of 3,500 acres raw land to productive farm land through the reuse of industrial effluent, the project has become an environmental showplace in which the State of Arizona and Abitibi Consolidated can take pride. It is a vivid example of how economic and environmental benefits can coexist within a large industrial facility.

BIO-DRAINAGE: TO CONTROL WATER LOGGING AND SALINITY IN IRRIGATED LANDS

A.S.Kapoor*

ABSTRACT

Irrigated agriculture faces the problem of water logging and salinisation. Presently practised drainage measures cause water pollution and environmental degradation. Bio-drainage, in which the property of transpiration of trees is used to strike a water balance and check the rise of ground water table above critical depth, can be an option to control water logging and salinisation of soils. In case irrigation water is of good quality, total minerals removed annually by crop and forest bio mass can match the total annual import of minerals with the irrigation water. A case study of Indira Gandhi Canal Project (IGNP), Rajasthan, India is presented.

Feasibility of bio-drainage and how water balance and salt balance can be achieved are described with the help of theoretical principles as well on the basis of research results and field experience. In case of the IGNP, forest plantations in no more than in about 10 percent area, can provide satisfactory insurance against water logging.

IRRIGATION, WATER LOGGING AND SALINITY

Large investments have been made, world over, in expanding areas under irrigation and this has made significant contribution to world food production. In dry arid regions, rain-fed agriculture gives poor returns while with irrigation there is many fold increase in agriculture productivity of lands. But irrigation in arid and dry regions very often leads to water logging and salinisation. There is an apprehension that salinisation of land is inevitable and irrigation schemes can have only a finite life, and cannot be sustained indefinitely.

The Sumerian Empire flourished about four thousand years ago in Mesopotamia, in the plains of rivers Tigris and Euphrates, on the base of highly developed irrigation system. Later, large scale salinisation rendered the farm lands unproductive and this contributed to the collapse of the Empire. In California's Imperial Valley, drainage water from irrigated lands is discharged into the Salton Sea, whose salinity is on the increase. Similarly discharge of drainage water from

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irrigated lands in San Joaquin Valley, California into the Kesterson Reservoir has resulted in problems of toxicity and discovery of selenium in the biota.

On the other hand, ancient civilisation of Egypt depending on irrigation from the river Nile has survived for thousands of years. Aswan Dam has brought about remarkable changes but extensive drainage systems have been constructed during the last two decades to overcome the water logging and salinisation problems.

In the Indus basin, in India and Pakistan, extensive water storage and distribution systems have been constructed since the Nineteenth Century. These have made great contribution to agriculture productivity but have led to problems due to inadequate drainage in some parts.

All major irrigation schemes face problems of water logging and soil salinity which must be faced and tackled by proper management. Failure to do so may jeopardize the sustainability of irrigated agriculture.

PRESENT STATUS OF DRAINAGE MEASURES

About one third of some 255 Mha. of irrigated area worldwide is threatened by water logging and salinity. Thatte et al, using FAO 1996 data estimate that an area of 60 Mha is water logged and about 20 Mha is salt affected. ICID (Schultz 1990) estimated that about 150 Mha of world's irrigated area has been provided with drainage facility, out of which about 30 Mha has been equipped with sub-surface pipe drainage system (horizontal drainage). It has been installed on a large scale in more than 35 countries including Canada, Egypt, Pakistan, Iran, Iraq, Mexico, Turkey, Malaysia and Uzbekistan (Chedieng and Visvanathan 1997).

In the fifteen countries of the European Union (Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, Luxemberg, Netherland, Denmark, Portugal, Spain, Sweden and the United Kingdom), the climate is mostly humid and oceanic temperate, with precipitation occurring evenly distributed throughout the year. The winter storage of precipitation in shallow soil cover over an impervious barrier results in perched water tables, more often in Belgium, France, Germany and the United Kingdom. In some regions the groundwater tables are already high due to the influence of rivers or sea and precipitation causes further rise resulting in permanent problem of water logging as along coastal areas, alluvial valleys and in the Netherlands. It is only in the southern part of Europe that irrigated areas may encounter salinization hazard.

Leasaffre et al (1995) report that agriculture intensification drive in Western Europe resulted in land improvement and more than 50 percent of water logged areas were reclaimed by sub-surface drainage. This resulted in over production of cereals and a policy change was made in year 1992 to set aside roughly 15 percent of the arable land.

The detrimental effects of drainage towards environment were recognised and drainage was restricted, even prohibited in wet biotopes, such as uncultivated marsh lands, small ponds and alluvial plains. The annual rate of installation of sub-surface drainage that was about 3,00,000 ha during the 80's came down about one-half in the 90's. In some places (Germany and U.K.etc.), drained areas were converted back to marshlands. In several countries (Netherlands, Switzerland, Germany etc.) investments on drainage are restricted to rehabilitation of ancient systems.

In the wet humid regions of North America, drainage is required to remove excess soil water, especially on poorly drained soils. Of the 53 million ha. of cropland drained in North America (45 million in the U.S. and 8 million in Canada), about one-third is sub-surface drained. Total annual precipitation (snowmelt and rain) exceeds evapotranspiration.

In Egypt a special authority called the Egyptian Public Authority for Drainage Projects (EPADP) was established in 1973. Sub-surface drainage systems have been installed in 1.9 Mha area out of 2.7 Mha irrigated area. Drainage in financed by the State, but the farmers have to pay back the investment over 20 years period at no interest which amounts to more than 50% subsidy.

In Pakistan, drainage has been implemented on some 1.0 Mha out of 15.4 Mha of irrigated area including 0.23 Mha with pipe drainage and 0.5 Mha with vertical well drainage system. An additional 4-6 Mha area is estimated to require drainage facility.

In Western U.S.A. 25 to 30% irrigated area is reported to be provided with sub-surface drainage (Rao, KVGN 1998).

In India, which had 50 Mha irrigated area in 1993 (CWC 1996), sub-surface drainage has been installed in less than 0.02 percent area (Rao, 1998).

TREE WATER USE

The reported results of capacity of trees to grow and transpire water show great variance. This is not surprising because of the many factors, influencing the rate of transpiration. It is quite difficult to carry out experiments under controlled conditions to determine the rates of transpiration. But fairly dependable data is available on rate of evapotranspiration from crops (ETo) and rate of evaporation from free water surface (Apan). Crop evapotranspiration (ETo) is defined as the rate of evapotranspiration from an extensive surface of 8 to 15 cms tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (FAO Paper No.24). Apan is the observed rate of evaporation from water surface in a pan of standard size and is generally 1.15 to 1.20 times of ETo.

The published annual tree water use values range from 0.6 Apan for irrigated Eucalyptus with full canopy cover in Western Australia (Marshall and Chester 1991) to 1.9 Apan for *Eucalyptus* Camaldulensis irrigated with seepage affluent (Morris and Wefner, 1987). Diwan, quoting Greenwood et al (1979) reports *Eucalyptus* Globulus and Camaldulensis at the age group of 11, 16 and 24 months transpired about 0.8, 6.8, 37 and 0.4, 8.5, 21 litres per day per tree respectively of the two species.

In a study in California, U.S.A., total evapotranspiration from tree plantations during 220 days (April-November 1990) was estimated as 1153 mm, which was nearly equal to the applied water.

Grattan et. al. report that the extent to which *Eucalyptus* can reduce drainage volumes depends on maintaining high rates of evapotranspiration. In non-stressed environments, the literature reports crop coefficients (Kc) for a full cover of *Eucalyptus* trees between 1.2 to 1.5 (Stribbe 1975; Sharma 1984). However *Eucalyptus camaldulensis* was irrigated with saline drainage water (Ec = 10 ds/m and 12 mg/l B), evapotranspiration (ET) was estimated using two energy balance methods and Kc values were 0.83 (i.e. ET of *Eucalyptus* was 0.83 reference crop ET) (Dong et. al. 1992).

In a study in desert area of Rajasthan, India, annual evapotranspiration from tree plantations with a density of 1900 trees/ha was estimated as 3446 mm which is about 1.2 Apan.

Chhabra et al (1998) report the results of a study carried out at Central Soil Salinity Research Institute (CSSRI), Karnal, India Lysimetres of 1.2 m diameter and 2.5 m depth made of R.C.C. were filled with sandy loam and planted with eucalyptus (Eucalyptus tereticornis). The water table was maintained at 1.0, 1.5 and 2.0 m from the surface and ground water salinity at 0.4, 3, 6, 9 and 12 ds/m. The eucalyptus plant bio drained 2168, 3057, 3673, 3382 and 3357 mm water during the 1st, 2nd, 3rd, 4th and 5th year from non-saline ground water and a water table depth between 1.0 m to 2.0 m. At salinity levels of 3, 6, 9 and 12 ds/m, the eucalyptus plant bio drained 81, 64, 63 and 53 percent of that under non-saline conditions.

Colder I.R. et al (1994) on the basis of studies in Karnataka, India, report measurements on young eucalyptus plantations and establish a close corelation between the transpiration rate of an individual tree and its stem cross-sectional area as follows:

Basal (stem) area (m2)	*0*	*0.002*	*0.004*	*0.006*	*0.008*	*0.01*
Transpiration rate	*0*	*0.01*	*0.025*	*0.040*	*0.050*	*0.062*

Under the same study, the annual water use of (eucalyptus) forest was found to be higher than that of agricultural crops (about 2 times higher than finger millet).

Water hungry plants like *Eucalyptus* Camaldulensis, Acacia nilotica, Ziziphus spp., Delbergia sissoo, Prosopis Cineraria, Tecomnella undulata etc., on full development, with a tree density of 1100 trees/ha or more can be expected to transpire water in a year equal to annual Apan evaporation. *Eucalyptus* species are salt tolerant and grow faster than other trees and are therefore generally preferred, but some other species of trees can also give almost equally good results.

BIO DRAINAGE

All plants transpire water. The rate of transpiration depends primarily upon climatic condition, type and species of plantation, and availability of soil moisture in the root zone. Agricultural crops consume a major part of the irrigation water by transpiration but the water lost in percolation during field application and that lost through seepage in the conveyance system, goes down to the ground water reservoir. When the water table surface comes up sufficiently high, and is within the reach of roots of trees in plantations, the trees start drawing water from the ground water reservoir through the process of transpiration. This process of withdrawal of ground water by plantations is termed '***Bio-drainage***'.

Plantations, particularly in dry arid regions, can transpire large quantity of ground water and can be used to control rise of ground water table. Plantations also draw salts and minerals from the soil to some extent. Where the irrigation water is of good quality, plantations through bio-drainage can help achieve water balance as well as salt balance in the ground water regime.

BIO DRAINAGE FEASIBILITY

For bio-drainage to be effectively adaptable, following requirements are to be met:

(a) Water balance : The quantity of water removed from the ground water annually should equal the quantity of recharge.

(b) Salt balance : The quantity of minerals removed annually should be nearly equal to the quantity of mineral import.

(c)	Area under plantation	: Irrigation is practised primarily to promote agriculture, horticulture, dairy etc. Therefore in term of economic returns afforestation or agro-forestry should be comparable with that from other alternative uses of land. If it is not so, afforestation may still be justified, on considerations of the environmental and drainage benefits.
(d)	Water for plantations	: Under ideal situation, trees in afforestation area on full development should be able to draw most of their requirement of water from the ground water table, so that surface irrigation water can be put to other productive uses. If this is not possible, plantation trees would need some irrigation water. They may also need some water periodically to leach down salts from the root zone, if and when the salinity levels approach threshold limits.
(e)	Ground water quality	: The quality of ground water, when the water table approaches the root-zone of trees, should be such as can be tolerated by the plant species, otherwise the trees would need to be supplied irrigation water.
(f)	Effect on lowering ground water table	: Trees can lower the ground water table directly underneath the plantation area, to a depth up to which the tree roots can extend. This can be upto 15 m from ground surface or even more. To be effective as a drainage measure, the ground water table must be lowered in the irrigated area to a minimum critical depth (say 2 m below ground level), at the farthest point from the edge of the plantation area.

WATER BALANCE

Before the introduction of irrigation, the ground water system is in a state of equilibrium. The inflows, mostly from natural precipitation, seepage from water bodies and ground water in-flow match the outflows on account of withdrawal of water for agriculture and other uses, ground water out flow etc. There are some fluctuations in the water table level from season to season and from dry year to wet year, otherwise the ground water system over a period of time, reaches a state of equilibrium and remains fairly stable. With the advent of irrigation when a large quantity of water is brought from outside area, the state of equilibrium is disturbed and ground water table no longer remains stable. Depending upon the quantity of net incremental recharge, the ground water table starts rising and continues to do so until a new balance is reached. As long as balance is not reached, the water table continues to rise and may come up to ground surface or rise even higher, causing water logging. Ultimately, evaporation from ground surface in water logged area and from surface of formed water pools along with other withdrawals, strikes a balance with the quantity of recharge. But by this time, large areas may be lost from agriculture use, on account of water logging.

To overcome the above problem, the objective of any drainage scheme, is to achieve water balance before the ground water table rises up to the critical depth, which in general may be taken as 2.0 m below ground level. This would be possible if the annual rate of withdrawal from ground water equals or exceeds the rate of recharge, when or before the ground water table creeps upto the critical depth.

AREA UNDER PLANTATION FOR WATER BALANCE

It is described earlier that for stable water balance, total annual withdrawal of water Wb (=P x Apan), where P is the area under plantation and Apan is surface evaporation from standard pan, should equal the total annual recharge R (=Rc + Rp) where Rc is the net annual recharge from water conveyance system and Rp that in the field during water application.

Apan is largely dependent on climatic conditions and can be determined for any region by simple experiments. The efficiency of water conveyance system depends upon the method of water conveyance and physical conditions. In long unlined canals in permeable strata, conveyance losses can be very large. In lined canals and in impermeable strata, they are much less. In piped supply systems, the losses may be negligible.

The efficiency of water application in field can vary widely. In well levelled or graded fields with small border strips or basins, high efficiencies of field application can be achieved. With sprinkler or drip methods of irrigation, the field losses can be minimised.

Some water is inevitably lost by evaporation during conveyance and field application. The net recharge to ground water from a reasonably managed surface irrigation system may range between 20-40 percent of the total irrigation supply. It would be significantly less with sprinkler and drip irrigation systems and can be higher in poorly managed surface irrigation systems. Let the ratio of net recharge to ground water to the total irrigation water supply be called Recharge Factor R_F.

Irrigation water is supplied to crops to meet evapotranspiration requirement (ETcrop). Following the procedure described in FAO paper No.24, Reference Crop Evapotranspiration (ETo) is generally determined by modified Penman method. Appropriate value of crop coefficient (Kc), which depends upon crop characteristics, time of sowing, stage of crop development and climatic conditions is determined. ETcrop is then taken equal to Kc x ETo. The irrigation requirement is decided after allowing for effective precipitation (rain fall) during the crop period. The gross irrigation requirement (I_R) is determined taking into account the water conveyance and field application efficiencies.

All culturable land is not irrigated and put to agriculture use through out the year. In dry arid regions where quantity of available water is limited and the area of available culturable land is relatively very large, the area under irrigation and agriculture, at any point of time, is less than one-half of the whole culturable area. Very often, two crops are raised in a year. The total cropped area, counting area under both winter and summer crops, may generally range between 80 percent to 150 percent of the culturable area. In desert areas, lower intensities of irrigation of up to about 60 percent have been practised. Let the intensity of irrigated agriculture be represented by the factor A_F.

Therefore, if total culturable area be 'C', the annual irrigation water supply would be $C \times A_F \times I_R$ and the net recharge to the ground water would be $R_F \times (C \times A_F \times I_R)$.

If the entire quantity of recharge is to be withdrawn by bio-drainage, the requirement of area under afforestation (P) would be ;

$$P = \frac{R_F \times (C \times A_F \times I_R)}{\text{Apan}}$$

or

$$\frac{P}{C} = \frac{R_F \times A_F \times I_R}{\text{Apan}}$$

Where

P/c	represents the fraction of culturable area that must be under afforestation
R_F	is the recharge factor i.e. ratio of net recharge (to ground water) to total irrigation water supply
A_F	is the area intensity factor of irrigated agriculture
I_R	Gross irrigation requirement

Apan is surface evaporation from a standard pan

The position is depicted in *Figure 1*.

As an illustration, if $R_F = 0.3$, $A_F = 1.0$, $I_R = 600$ mm and Apan = 1500 mm, P/c would be 0.12, that is 12 percent of culturable area under afforestation can provide the needed bio-drainage.

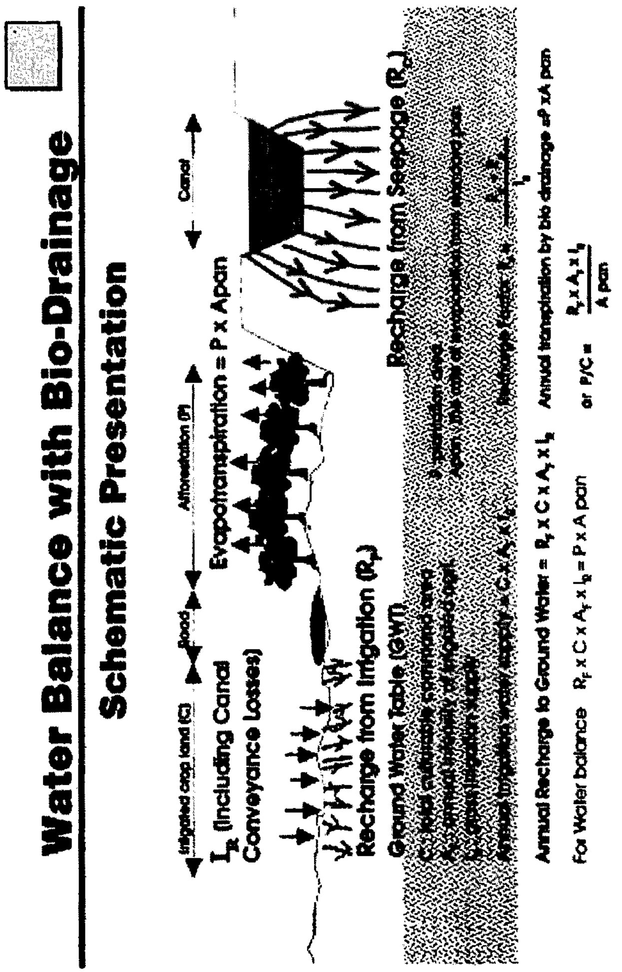

Figure 1.

SALTS IN IRRIGATION WATER

The major source of salt input in an irrigated region, is the salt content in irrigation water imported from outside the region. As long as the water table is deep, the salts are washed down by the percolating water to the ground water. But when the ground water table rises and comes up near the ground surface, the salts contained in the ground water as well as in the irrigation water contribute to salinisation of the soil.

While considering salt balance, at the beginning of irrigation, the impact of weathering, oceans and winds, except in special situations and conditions, can be ignored. The salt content in ground water does not affect salinity levels of soils for agriculture as long as it is deep. The net import of salts with irrigation water can be estimated with the knowledge of salt content and volume of irrigation water.

Composition of Average River Waters of the world is shown in Table 1. Most natural water in rivers is of very good quality for use in irrigation. The mineral content and electrical conductivity values are quite low. But the natural quality of river water can be greatly affected by the reduction in quantity of normal flow, discharge of pollutants, industrial affluents, irrigation saline drainage water into the river stream and other human activities.

Table 1: Composition of Average River Waters of the World[a]

Region	Ece[b] (μ mhos/cm at 25°C)	Total Concentration		B mg/l)	Ca	Mg	Na	K	Alkalinity[c]	So_4	Cl	No_3	SAR
		mg/l	meq/l						(meq/l)				
North America	220	142	1.89	-	1.05	0.41	0.39	0.04	1.11	0.42	0.23	0.02	0.5
Europe	270	182	2.28	-	1.55	0.46	0.23	0.04	1.56	0.50	0.19	0.06	0.2
Australia	95	59	0.58	-	0.19	0.22	0.13	0.04	0.52	0.50	0.28	trace	0.3
World	190	120	1.42	-	0.75	0.34	0.27	0.06	0.96	0.23	0.22	0.02	0.4

[a]Adopted from Rhodes and Bernstein, 1971
[b]Electrical conductivity
[c]Alkalinity is titrable bases made up mostly of HCO^-_3, with small amounts of CO_3^{-2} and OH
Source : James David.W 'Modern Irrigated Soils' (1982)

QUANTITY OF SALTS IN IRRIGATION WATER

The amount of dissolved salts in irrigation water is generally expressed as total dissolved solids (TDS) in milligrams per litre (mg/l) and as electrical specific conductance i.e. the conductivity per unit volume (1 cm^3) of saturated solution in siemens (s) per cm.(ds/m = ms/cm = m mhos/cm)

If V (in cubic metres) be the volume of imported water used for irrigation containing m_w (in mg/l or g/m^3) minerals constituents, the total quantity of minerals brought in by irrigation water would $m_w V \times 10^{-6}$ tons.

MINERALS IN PLANT BODY WEIGHT

According to Palladin, the bulk of dry weight of a plant is made up of :

Carbon	45.1 percent
Oxygen	42.0 "
Hydrogen	6.5 "
Nitrogen	1.5 "
Mineral constituents	5.0 "
Total :	100.0 "

Pandey & Sinha give average chemical composition of plant body by weight as follows :

Carbon	20.0 percent
Oxygen	62.0 "
Hydrogen	10.0 "
Nitrogen	3.0 "
Mineral constituents	5.0 "
Total :	100.0 "

It would therefore be reasonable to assume that mineral constituents in a plant, which are all derived from the soil water, form about 5 percent of the dry body weight of the plant. In case more dependable data on mineral content in plants is available for a site under consideration, it would be advisable to use such data.

QUANTITY OF MINERALS REMOVED BY CROPS AND PLANTS

If total annual utilisable dry bio-mass produce from agriculture in an irrigated area be 'A' (in tons) and that from afforestation over an area 'P' (in ha) at the rate of 'b' tons/ha/year be P x b, then the total quantity of minerals removed from the soil by crops and trees would be $(m_c \times A) + (m_p \times b \times P)$,where m_c and m_p are percentage mineral contents in crops and plantations respectively, that are grown in the area.

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SALT BALANCE

In case the annual import of minerals ($m_w V \times 10^{-6}$) exceeds the total annual extraction and removal which is ($m_c \times A$) + ($m_p \times b \times P$) the salinity in soil and/or ground water would progressively increase. On the other hand, if annual extraction and removal of minerals exceeds the quantity of annual import, the salinity in soil and/or ground water should decrease progressively and there would be no threat to sustainability of irrigated agriculture on account of increase in soil salinity, if the rise of ground water table is kept in control.

It is possible that even though salt balance may be achieved by accounting for all minerals taken together, it may not be so in respect of all individual elements. The important common cations in water and plants are Calcium, Sodium, Magnesium and Potassium. Exercise for salt balance in respect of each individual element can be done in the same manner as for total minerals, by using the respective 'element content values' in place of 'mineral content values' in the above equations.

In case of imbalance, the rate at which mineral (or element) content in ground water would be expected to rise can be estimated and the period it is likely to take to reach threshold limits can be forecast. This in turn can help to assess the feasibility and expected life-span of the proposed measures and throw light on additional supplementary steps that need be taken.

A CASE STUDY

Irrigation Development in Indira Gandhi Nahar Project (IGNP), India

The IGNP has been receiving water for irrigation since the year 1961. The figures of actual annual irrigated area are shown in Table 2.

Table 2: Development of Irrigation in IGNP

Year	Area Irrigated (in thousand hectares)		
	Stage I	Stage II	Total
1975-76	289	-	289
1985-86	463	2	465
1995-96	664	137	801
1996-97	682	159	841

Down stream areas having not been opened for irrigation, the quantity of available water for the limited opened area has so far been quite liberal. During the period 1988 to 1995, the average rate of water use, released at the head of feeder canal, was 1260 mm against the designed value of 560 mm. The values for neighbouring project areas of Gang and Bhakra commands, during the same period, were 575 and 515 mm. respectively.

WATER LOGGING

The depth of water table in the command of Stage I in the year 1952 generally varied between 40 to 50 meters below ground level (bgl). With introduction of irrigation the ground water table started rising. During the decade 1981-82 to 1991-92, the average annual rate of rise of water table was 0.92 m.

In Stage II of the project, the ground water table before advent of irrigation generally ranged between 20 to 100 m bgl. With irrigation it has been rising though not with the same rate as in Stage I.

A survey conducted in the year 1991 indicated that the total number of locations where pools of water were formed on both sides of the canal was 127 and the total area where the water appeared on the surface was 900 hectares. Because of the plantations subsequently raised along the canals, and around the pool areas, there has been progressive reduction in the affected area and in June, 1997, there were only 8 locations of water pools with a total area of 20 ha. The position of progressive reduction in affected area is shown in Table 3.

Table 3: Indira Gandhi Main Canal Rd 750-1365 Area with Ground Water at Surface

Location	June 91	June 93	June 95	June 97
RD 750 - 861	254	35	24	10
RD 860 - 961	83	-	-	-
RD 961 - 1121	533	471	83	4
RD 1154 - 1365	30	24	20	6
Total	900	530	127	20

Area in ha.
RD - Unit of 1000 Ft. = 328m.

<u>Plantation in the reach RD 952-957 (Km 290-291.7) Left side</u>

A 1524 m long and 261 m wide strip along the left side of the main canal from RD 952-957 (Km 290 to 291.77), was selected for detailed study. The plantation work was carried out during the years 1987 to 1994. A field census was carried out and the distribution of different species of actually growing trees in July ,1997 is shown in Table 4.

Table 4: Distribution of Different Species of Growing Trees Along Left Bank of Main Canal RD 952 – 957

S.No.	Location	Number of growing trees of species							
		Eucalyptus camaldulensis	Acacia nilotica	Azadirachta indica	Ziziphus spp.	Delbergia sisso	Prosopis Cineraria	Tecomnella undulata	Total No. of Trees
1.	RD 952.00 to RD 952.200	396	1077	-	134	-	-	-	1607
2.	RD 952.200 to 952.450	566	902	-	93	-	-	44	1605
3.	RD 952.450 to 953.00	3296	3411	36	27	-	133	-	6903
4.	RD 953.00 to RD 953.250	1465	325	-	-	-	-	-	1790
5.	RD 953.250 to RD 953.500	1527	494	-	115	-	-	-	2136
6.	RD 953.500 to 953.800	1090	643	-	380	-	-	-	2113
7.	RD 953.800 to 954.00	659	580	-	-	-	-	-	1248
8.	RD 954.00 to 955.00	6950	3352	-	-	506	648	-	11456
9.	RD 955.00 to RD 955.300	1220	870	-	153	22	-	83	2348
10.	RD 955.300 to RD 955.500	995	285	-	414	3	-	-	1697
11.	RD 955.500 to RD 956.00	2932	1238	-	219	-	-	159	4545
12.	RD 956.00 to RD 957.00	7137	2022	-	-	-	214	386	9759
	Total	28233	15208	36	1535	531	995	672	47210

FORMATION OF WATER POOLS ALONG THE CANAL RD 952-957

The canal was first filled with water in the year 1983. Soon after, pools of water were formed on both sides of the canal. The maximum water pool area on the left side of the canal in this reach was 25 ha (year 1988). The plantation work was taken in hand in the year 1987 along the canal and around the water pool area. With the growth of trees, the water pool area reduced progressively as follows:

Year	Water pool areas (ha)
Up to year 1988	25
1989	23
1990	20
1991	15
1992	9
1993	2
1994	-

The deepest pool bed was about 3.5 m lower than the natural ground surface level (NSL). In April 1994, the ground water went down to 4.9 m below the NSL in April 1996, to 8.8 m below NSL in Sept 96, to 10.3 m below NSL and in July 1997, to 12.9 m below NSL. At Cross-section at RD 953.2, the ground water level has gone down by as much as 15 m.

Peizometers were installed in year 1997 to determine the ground water profile at two cross-section across the canal. The position of observed water levels and other details are shown in *Fig. 2.* Annual rate of transpiration from the plantations was estimated as 3446 mm.

DISTANCE UP TO WHICH PLANTATIONS CAN PROVIDE EFFECTIVE BIO-DRAINAGE

If there are two plantation areas separated by distance L, the depression of water table underneath them would result in ground water flow behaviour similar to that as in case of flow towards parallel ditches penetrating an unconfined aquifer. On equilibrium, the position would be as shown in *Fig. 3,* and the relationship between depression of ground water table, rate of recharge, hydraulic conductivity, depth to barrier layer and distance between plantations can be expressed by Donnan equation (DONNAN-1946) :

$$L^2 = \frac{8\,k\,yo\,h}{R} + \frac{4\,k\,h^2}{R}$$

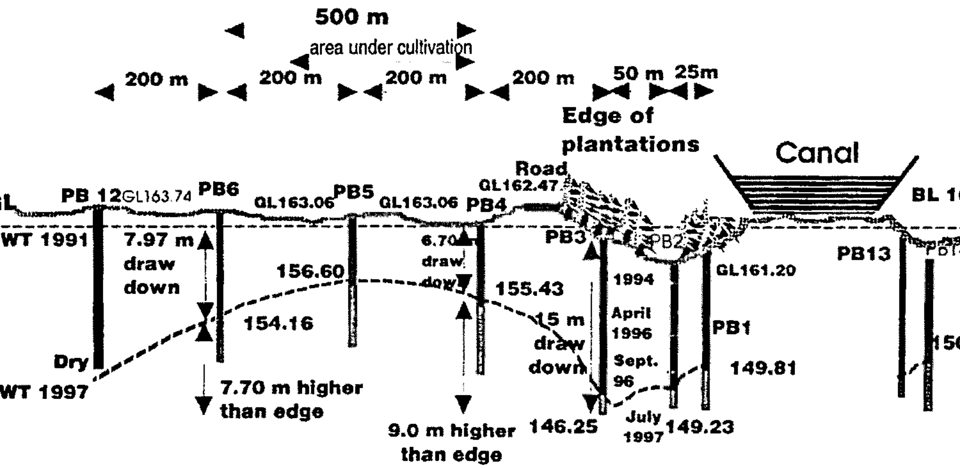
Where

L= distance between plantations
R= rate of recharge
Yo= height of water level above barrier layer underneath plantations
k= hydraulic conductivity
h= head difference

Ground Water Level Fluctuations in Piezo Meters

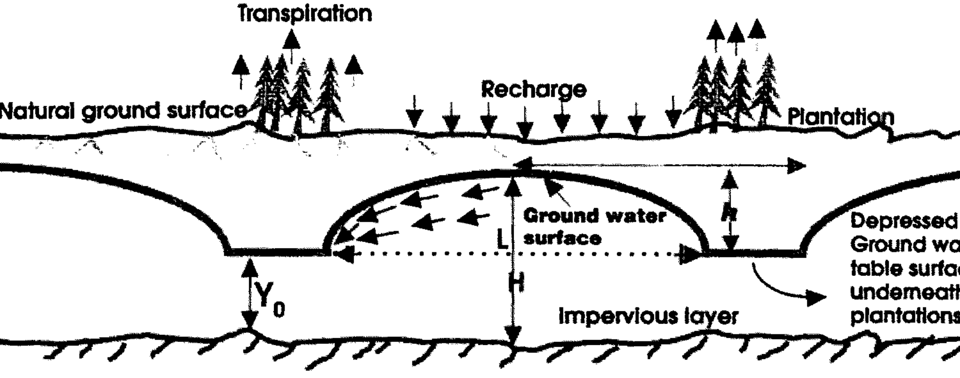
at RD 953-212 of IGMN

Cross Section



Flow towards Depressed Ground Water Table

Under Plantations



Donnan Equation $$L^2 = \frac{8KY_oh}{R} + \frac{4Kh^2}{R}$$

With R = 0.5 mm/day, h = 10.0 m, Y_0 = 10.0 m and K = 100 mm/day, L works out to 500 m.

L : distance between plantation
R : rate of recharge
Y_0 : height of water level
K : hydraulic conductivity
h : head difference

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PREDICTION OF SEDIMENT TRANSPORT RATE IN IRRIGATION CANALS USING MODIFIED LAURSEN METHODOLOGY

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Maurice L. Albertson[4]

ABSTRACT

An improved method for predicting sediment transport in alluvial channels has been developed based upon modifications of the Laursen (1958) equation and based upon a wide range of field data. The applicability of this new method was tested for irrigation canals. The following canals were selected for the study: ACOP in Pakistan, American canals, Canal del Dique, CHOP in West Pakistan, India canals, and the Rio Grande Conveyance Canal, which have a range of flow depth from 0.67 m to 5.13 m and width from 3.19 m to 140.21 m. Comparisons between computed results from the modified formula and field data verify that the new method can be utilized to compute total bed-material load in canals.

INTRODUCTION

Many researchers have observed that more than one value of sediment transport can be obtained from the same values of Q, u, S_w, S_f, and τ, Simons and Senturk (1992) and Yang (1996). Gilbert (1914) first reported the phenomena that different values of transport can occur for the same hydraulic parameters. He concluded that there was no correlation at all between water discharge and sediment discharge. Accordingly, the validity of the assumption that total sediment discharge for a given particle size could be determined by the proposed parameters was questionable. Yang (1996) stated that stream power τu, identified as the independent variable, has a strong correlation with bed material transport. Lane (1955) and Bagnold (1966) first proposed this concept that stream power has a strong correlation with sediment discharge. Furthermore, Yang (1996) suggested that unit stream power uS has a stronger relationship to bed material transport than stream power. Other researchers suggested that the stream power-type relationships could be utilized in straight channels as well as channels that

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are in the process of changing their patterns from straight to meandering or braiding (Yang, 1977 and 1996; Vanoni, 1978; Yang and Molinas, 1982). It is important to note that in dimensionless form, use of the unit stream power uS/ω, further improved the correlation with bed material discharge (Yang and Kong, 1991). Simons and Senturk (1992) reported that channel gradient is a variable difficult to measure precisely. They suggested that the stream power parameter could be improved by inclusion of a velocity parameter to replace the slope of the channel.

Kodoatie (1999) developed an improved methodology for predicting sediment transport in alluvial channels based upon utilization of a wide range of recirculating flume and field data. A total of 4,532 data sets from 33 river systems as well as 919 data sets from flume studies were utilized to develop a new sediment transport relation to estimate total bed material transport based upon modification of the Laursen (1958) method. Kodoatie adopted the Laursen methodology for analysis because this methodology was expressed in terms that permitted identification and separation of the various parameters, which are generally considered to cover the important variables, related to bed-material transport. .The Laursen equation is:

$$C_t = 0.01\gamma \sum_i p_i \left(\frac{d_i}{d}\right)^{7/6} \left(\frac{\tau_o'}{\tau_{ci}} - 1\right) f\left(\frac{u_*}{\omega_i}\right) \tag{1}$$

The river data utilized by Kodoatie was compiled by the following individuals: (1) Brownlie (1981) and Posada (1995) for the Mississippi, the Amazon, the Orinoco, and the Apure River Systems; (2) Williams and Rosgen (1989) for the Black, the Chippewa, the Chulitna, the North Fork Toutle, the Susitna, the Toutle, the Wisconsin, and the Yampa River Systems; and (3) Long and Liang (1995) for the Yellow and the Yangtze River Systems. Brownlie (1981) and Willcock and Southhard (1988) compiled the laboratory data utilized. The sets of field data were divided into two categories: Group 1 for developing the new proposed equations, and Group 2 for verification and validation. To develop these groups, the river data sets were divided into two groups in random order. Based on sediment size four river data sets were analyzed, including gravel-bed rivers, medium to very coarse sand-bed rivers, very fine to fine sand-bed rivers, and silt-bed rivers. The data were also divided according to the size of river in terms of width and depth. This division was based as follows:

1. small rivers with widths equal to or less than 10 m and depths equal to or less than 1 m,
2. intermediate rivers with widths greater than 10 m and widths equal to or less than 50 m and depths greater than 1 m and equal to or less than 3 m, and
3. large rivers with widths greater than 50 m and depths greater than 3 m.

MODIFICATIONS OF LAURSEN'S GRAPH

Madden (1985), utilizing Arkansas River data, modified Laursen's concepts. The modification by Madden permitted the analysis of bed material transport by size fractions. The Corps of Engineers' Waterways Experiment Station (1988) adopted this methodology for computing the transport in rivers with a mixture of sand and gravel forming the bed. Madden's modification to Laursen's methodology was based on three sets of special measurements made in the Arkansas River. The first two sets were gathered near Dardanelle in June and July 1957 and in April 1958. The third set was gathered near Morrilton in April 1958. Madden utilized the Missouri River data collected by Bondurant (1958) to validate the rating curves for the Arkansas River. The data sets resulted in best-fit curves that were parallel, but the two data sets did not overlap. The reader is reminded that the two sets of data were from two different rivers and even though they were sand-bed rivers, the methodologies produced by Bondurant and Madden were developed for specific rivers and are not generally applicable to other river systems. An adjustment factor related to the Froude number was utilized to modify the original Laursen equation by Madden (1985) as follows:

$$C_t = \sum_i p_b \left(\frac{d_i}{d}\right)^{7/6} \left(\frac{\tau_o'}{\tau_{ci}} - 1\right) f\left(\frac{u_*}{\omega_i}\right)\left(\frac{0.1616}{F_r^{\,0.904}}\right) \tag{2}$$

In addition, Copeland and Thomas (1989) proposed a modification of Laursen's (1958) concept. This methodology was formulated to be utilized in both sand-bed rivers and, to a lesser degree, in larger gravel-bed rivers. The modified Laursen equation as presented by Copeland (1989) is:

$$C_t = 0.01\gamma \sum_i p_i \left(\frac{d_i}{d}\right)^{7/6} \left(\frac{\tau_o'}{\tau_{ci}} - 1\right) f\left(\frac{u'_*}{\omega_i}\right) \tag{3}$$

Copeland and Thomas' modification to the Laursen concepts as applied shows their results in Fig. 1.

Kodoatie (1999) modified the Laursen graph using field data as illustrated in Fig. 2. At an earlier date, Bondurant (1958) proposed a modification of Laursen's concepts. Bondurant developed a relationship between (u_*/ω) and f(u_*/ω) in the Laursen graph from Missouri River data at Omaha and at Kansas City. At the lower portion of Laursen graph, Bondurant's (1958) modification fits quite well. However, between the upper portion and the lower part of the relation, the values of u_*/ω_i for the Missouri River data deviate sharply from those of the Laursen graph.

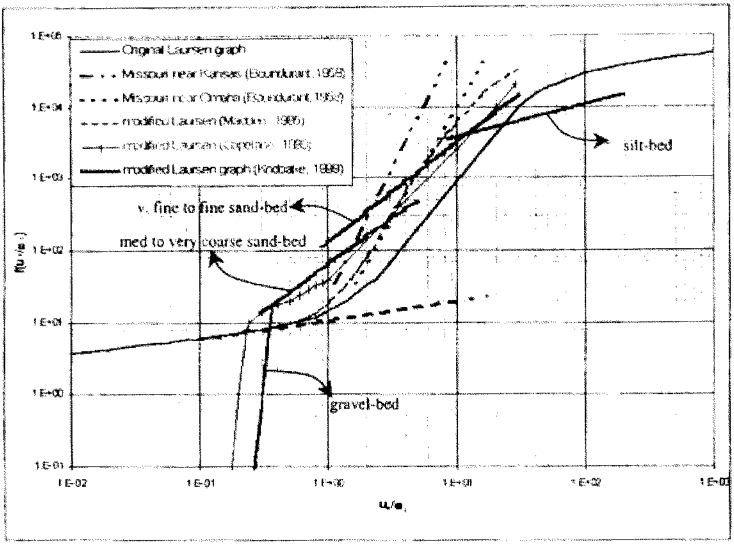

Fig. 1. Modifications of Laursen's (1958) Graph.

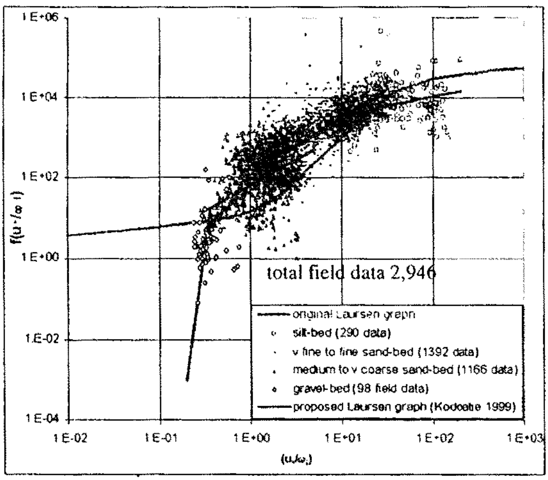

Fig. 2. Original Laursen and modified Laursen graphs by Kodoatie.

KODOATIE'S MODIFICATION OF THE LAURSEN METHODOLOGY

Kodoatie (1999) utilized a total number of data points (1,459) that pertained to transport of bed material. These data covered the range of particle size from gravels, medium to coarse sand, very fine to fine sand, and silt beds utilized only the dimensionless unit stream power uS/ω. Kodoatie verified that this parameter has a stronger correlation with bed material discharge than other stream power parameters. Figure 3a illustrates the scatter when stream power is plotted against measured concentration of suspended sediment. Figure 3b illustrates the scatter when unit stream power is correlated with measured concentration of suspended sediment. In both of these figures, there is significant scatter. In particular, the data points for gravel-bed rivers plot significantly above the data points for sand-bed and silt-bed rivers. Figure 3c verifies a much stronger relationship between measured concentration of suspended sediment and dimensionless stream power uS/ω. Additionally, the gravel-bed data commingles with the other data.

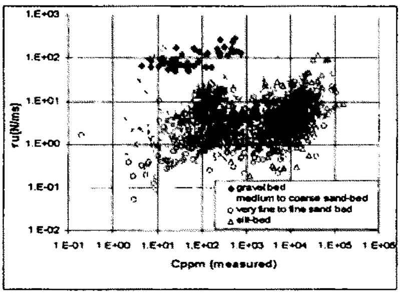

Fig. 3a. Stream Power τu

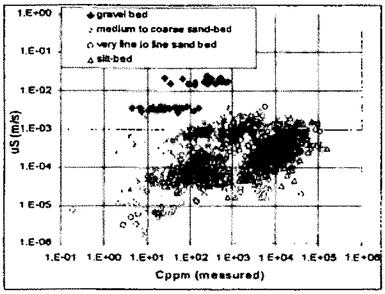

Fig. 3b. Unit Stream Power uS

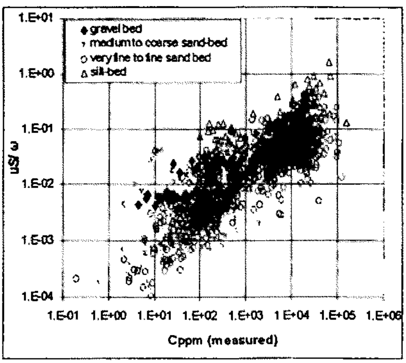

Fig. 3c. Dimensionless Unit Stream Power uS/ω

Fig.3. Relations Among C_{ppm} (Measured), Stream Power, Unit Stream Power, and Dimensionless Unit Stream Power.

Summarizing the three figures, significant variation in these relationships still exists. For the bed material ranging in size from fine to coarse sand, it is difficult to ascertain differences in bed material transport in the relationship between dimensionless stream power and measured suspended concentration. For example, Fig. 3c indicates the same concentration of measured sediment for fine sand-bed rivers and coarse sand-bed rivers. However, the reduction in diameter from gravel-bed rivers to silt-bed rivers tends to increase measured suspended sediment concentration. The Pearson Correlation Coefficients for the analysis illustrated in Figs. 3a through 3c are presented in Tables 1a, 1b, and 1c, respectively.

Table 1. Pearson Correlation Coefficient between C_{ppm} Measured and uS/ω, uS and τu for Various Rivers.

A. Gravel-bed Rivers

	Measured C_{ppm}	uS/ω	uS(m/s)	τu(N/ms)
C_{ppm}measured	1			
uS/ω	0.71	1		
uS(m/s)	0.69	0.95	1	
τu(N/ms)	0.67	0.82	0.88	1

B. Medium to Coarse Sand-bed Rivers

	Measured C_{ppm}	uS/ω	uS(m/s)	τu(N/ms)
C_{ppm}measured	1			
uS/ω	0.58	1		
uS(m/s)	0.45	0.9	1	
τu(N/ms)	0.33	0.23	0.29	1

C. Very Fine to Fine Sand-bed Rivers

s	Measured C_{ppm}	uS/ω	uS(m/s)	τu(N/ms)
C_{ppm}measured	1			
uS/ω	0.74	1		
uS(m/s)	0.76	0.87	1	
τu(N/ms)	0.18	0.40	0.46	1

Table 1, continued

D. Silt-bed Rivers

	Measured C_{ppm}	uS/ω	uS(m/s)	τu(N/ms)
C_{ppm}measured	1			
uS/ω	0.45	1		
uS(m/s)	0.62	0.79	1	
τu(N/ms)	0.30	0.74	0.78	1

In summary, the dimensionless unit stream power has the best correlation with measured suspended sediment C_{ppm}, see Fig. 3c. The strength of the correlation is exhibited in Fig. 4. This figure illustrates the range of dimensionless unit stream power and dimensionless flow depth compared to measured C_{ppm}. The dimensionless unit stream power utilizing regression analysis and nonlinear optimization techniques can add other variables to Equation 4 resulting in:

$$C_t = 0.01\gamma\left(\frac{d_{50}}{d}\right)^{7/6}\left(\frac{\tau_o'}{\tau_{c50}} - 1\right)10^{f\left(\frac{u_*}{\omega_{50}}\right)}\left(\frac{uS}{\omega}\right)^{a} \tag{4}$$

where a is a variable related to mean bed material diameter as shown in Table 2.

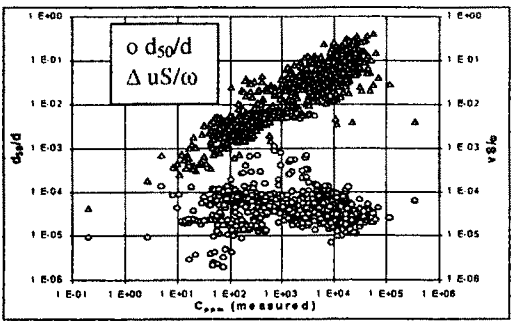

Fig. 4. Range of Dimensionless Unit Stream power and Dimensionless Flow Depth Compared to C_{ppm} Measured.

Equation 4 has been utilized to develop Fig. 5 illustrating the relationship u_*/ω versus $\log(u_*/\omega)$.

Table 2. Value of "a" in Equation (4) for Various Bed Materials.

Bed Material	"a"
Gravel	0
Medium to very coarse sand	-0.2
Very fine to fine sand	0.078
Silt	0.06

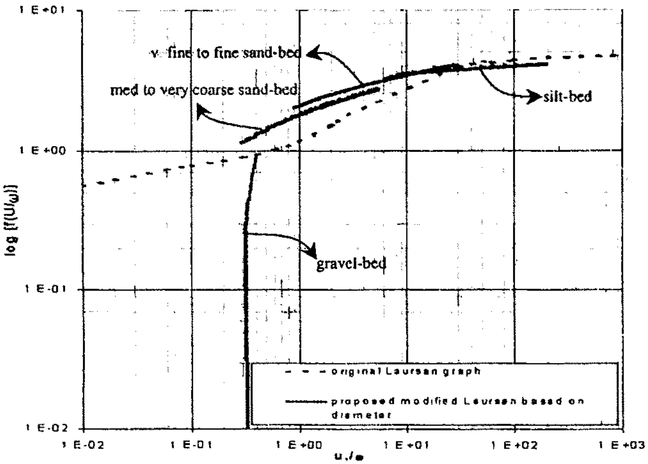

Fig. 5. Proposed Graph by Kodoatie Using Equation (4).

The modified Laursen equation by Copeland was applied by Raphelt (1996) to 10 rivers including: the Toutle, North Fork Toutle, Susitna, Tanana, Oak Creek, Clearwater, Chippewa near Durand, Chippewa near Caryville and Granite Creek Rivers. Utilizing these data, which included 187 sets illustrating conditions in gravel-bed rivers, 147 computed data points were greater than measured values, and 39 data points were within the range of acceptable accuracy, as illustrated by the discrepancy ratio comparing computed measured values. The discrepancy ratio for these data had a range of 0.2 to 5. One set of data points was below an acceptable range of accuracy. Raphelt concluded that the modified Laursen equation by Copeland significantly over-predicted gravel-bed material transport when applied by size fraction. The maximum over prediction was as much as 6,000 times higher than the measured value. The data falling within the range of acceptable accuracy all were for either sand- or very fine gravel-bed streams. The reduction of the critical dimensionless shear stress without taking into account the probability of grains to move and without including a hiding factor are probably the major reasons for over-prediction of bed material transport for those streams with $D_{50} > 4.00$ mm. The modifications to the Laursen equation by Madden, Copeland and Kodoatie are presented in Table 3.

Table 3. Comparison of Modified Laursen Equations

1	Used the same equation; added adjustment factor related to Froude Number	1	Used grain hydraulic roughness instead of grain shear stress	1	Used same equation but added dimensionless stream power as the adjustment factor
2	Used modified graph	2	Used modified graph	2	Used modified graph; more specific in particle bed diameter from silt to gravel
3	Used size fraction	3	Used size fraction	3	Used uniform particle diameter (no fraction)
4	Used Arkansas River data	4	Used both river and flume data (not specified)	4	Used 33 river systems and 18 sources of flume data (more than 5,300 total sets)
5	Graph is higher than original for sand bed; not specified for gravel and silt	5	Graph is higher than original for sand bed; for silt not specified; graph for gravel is smaller than new proposed	5	Graph is higher than the original for sand bed (sand bed is more specific for very fine to fine sand and medium to very coarse sand); smaller for silt compared to original; graph for gravel is proposed

APPLICATION OF THE MODIFIED LAURSEN EQUATION TO TRANSPORT IN CANALS

In order to ascertain the effectiveness of the Kodoatie (1999) equation, it was applied to data sets obtained from irrigation canals. A total of 334 sets of canal data were selected and utilized to test this equation. The data were collected from an array of canals as follows:

- ACOP Canals (West Pakistan)
- CHOP Canals (West Pakistan)
- American Canals (Colorado, Wyoming, Nebraska)
- Canal del Dique
- India Canals
- Rio Grande Conveyance Channel

ACOP Canals

A total of 151 sets of canal data were collected Mahmood, et al. (1979) from five canals in West Pakistan. However, only 142 complete sets of data were utilized in this study.

American Canals

Simons (1957) collected 24 sets of data from canal systems. The canals utilized in Colorado include: Bijou 53 & 54, Fort. Morgan I, II, III; IV, and V; in Wyoming: Laramie I and IV, Garland I and II, Lucerne I and II, North Plate Ditch, the Farmers Canal, In Nebraska: Central Nebraska Public Power & Irrigation and Drainage Canal, Lateral A29.1, the Cozad Canal, the Dawson Canal and the Taylor Canal. Twelve of completed sets of canal data were utilized in this analysis.

Canal del Dique

A total of 61 sets of data were collected in th is canal located in Columbia, South America by Nedeco (1973). Thirty two of these sets of data were utilized in this analysis. The data were collected at 10 stations along this canal.

CHOP Canals

A total of 33 data sets were collected from nine canals in West Pakistan. These data sets were collected by Chaudry, et al (1970) under the auspices of the Canal and Headworks Observation Program (CHOP) of the West Pakistan Water and Power Development Authority, 1962 – 1964, Lahore, West Pakistan.

India Canals

Chitale (1966) collected and reported 32 sets of canals in India.

Rio Grande Conveyance Channel

A total of nine sets of data were collected by Culbertson, et al (1972) at a station called Oak Creek.

The Range of Data Utilized From Canals

The range of data data utilized from canal studies include:

- discharge : 1.15 – 567.00 m3/s
- width : 3.19 – 140.21 m
- depth : 0.67 – 5.13 m
- D_{50} : 0.020 (silt-bed) – 0.715 (sand-bed)
- Slope : 0.000003 – 0.00111

Analysis of Selected Canal Data

Kodoatie's modification of Laursen's equation was utilized to compare computed results with measured field data. Statistical methods were utilized including the mean discrepancy ratio $\overline{R_D}$ (Bechteller & Vetter, 1989; Nakato, 1990; Yang and Wan, 1991; Hydrau-Tech, Inc., 1998 and Wu, 1999) and the correlation coefficient C_c (Hydrau-Tech, Inc., 1998). The equations for each of these two statistical parameters follow.

$$\overline{R_D} = \sum \frac{R_i}{N}, \qquad R_i = \frac{X_i}{Y_i} \tag{5}$$

$$C_c = \frac{\sum (X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum (X_i - \overline{X})^2 \sum (Y_i - \overline{Y})^2}} \tag{6}$$

For perfect correlation, the above statistical parameters utilizing Eq. (5) and Eq. (6) require that $\overline{R_D} = 1$ and $C_c = 1$. The results of the analysis comparing measured C_{ppm} with computed C_{ppm} are shown in Figs. 6a, b, and c. The discrepancy ratio and Pearson correlation coefficients for three ranges of bed-material sizes dictated by the canal data analyzed are illustrated in Table 4. From Fig. 6 and Table 4, it is concluded that the original Laursen equation over-predicts for silt-bed canals, and under-predicts for sand-bed canals. This figure and table illustrate that the comparison of measured concentration with predicted concentration using the Kodoatie modification of Laursen's equation gives much improved results.

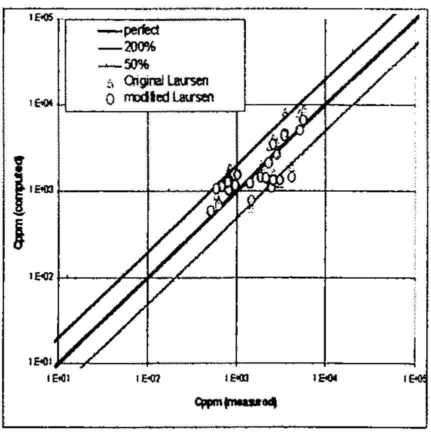

Fig. 6a. Silt-Bed Canals.

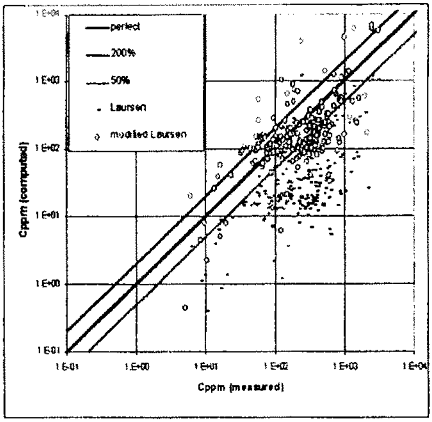

Fig. 6b. Very Fine to Fine Sand-Bed Canals.

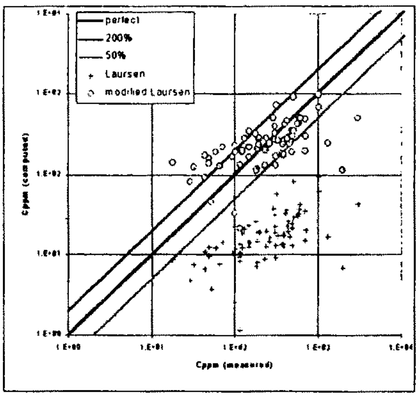

Fig. 6c. Medium to Very Coarse Sand-Bed Canals.

Fig. 6. C_{ppm} Computed and C_{ppm} Measured Data Utilizing Laursen And Modified Laursen.

Table 4. Discrepancy Ratio $\overline{R_D}$ and Pearson Correlation Coefficient C_c Between C_{ppm} Measured and C_{ppm} Measured Using Original Laursen Equation and Modified Laursen Equation

Type of Canal Bed .	C_c Original	C_c Modified	$\overline{R_D}$ Original	$\overline{R_D}$ Modified
Silt	0.81	0.79	1.26	1.01
Very fine to fine to sand	0.65	0.64	0.06	1.15
Med. to very coarse sand	0.41	0.41	0.09	1.27

CONCLUSIONS

The utilization of such an extensive array of data encompassing a wide range of dimensions, gradients, and sizes of bed material has not been accomplished in past research. It is emphasized that:

- The geometry of a canal is selected based upon the type of bed and bank material, flow, variation in flow, and duration of range of flows as dictated by the irrigation/utilities' demand based upon season and climate.

- Unlined canals must be cognizant of the potential for erosion, aggradation and/or deposition.

- The proposed methodology for estimating transport of sediments in erodible canals is considerably improved over existing relationships. However, the transport of sediments in stable alluvial canals is only an improved estimate. In addition, it is recommended that the sorting of sediment through the canal should be done by size fractions to estimate changes in the median diameter of bed material with time and distance.

- Canals may have sediment-laden water and/or clean water at their headworks. If the supply of water and sediment are dependent upon the characteristics of the river, the design, and the operation of the diversion structure, etc., exclusion and ejection structures must be integrated into the design of the headworks.

- It is also concluded that during flood stages in the river the headworks should be closed if at all possible. Otherwise, considerable sediment may be permitted to enter the canal where it will deposit within a short distance of the headworks. This deposition could possibly reduce the capacity of the canal, and, as another alternative, steepen the gradient in a depositional area sufficiently to increase velocities to a level where considerable bank erosion may occur.

RECOMMENDATIONS

- There is a wide variation in predicted sediment transport in canals. Therefore, sediment exclusion and/or sediment ejection facilities may be required to refine the sediment supply to acceptable limits for a specific canal.

- Regime relations are recommended to estimate channel geometry for canals without linings constructed in erodible soil, Simons and Albertson (1963).

- The regime of the canal may change over time as a consequence of sorting of the natural soil that the canal is constructed within and the introduction of sediments at the headworks from the river into the canal.

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NOTATION

ρ	density of water
ω	fall velocity
γ	specific weight of water
τ_{ci}	critical shear stress for sediment size d_i
ω_i	fall velocity of the sediment size d_i
ωi	fall velocity of particle dimeter of the i^{th} size
τ_o	shear stress
τ_o'	bed shear stress due to grain size
τu	stream power
C_c	correlation coeficient and is defined by Equation (2.75)
C_i	concentration distribution in Equation (2.19)
C_t	total average sediment concentration in weight per unit volume
d	flow depth
D_{50}	mean diameter of sediment
d_i	geometric mean diameter of particle of the i^{th} size
F_r	Froude number
$f\left(\frac{u_*}{\omega_i}\right)$	functional relation of u_*/ω_i

$f\left(\frac{u'_*}{\omega_i}\right)$	functional relation of u_*'/ω_i, Plate 16 Copeland & Thomas (1989)
i	data set or point number
N	total number of data sets
p_{bi}	fraction of bed material of d_i
p_b	fraction of bed material
p_i	fraction of bed material for diameter particle size d_i
R_i	ratio of computed sedimentation and measured sedimentation
$\overline{R_D}$	mean discrepancy ratio
S	channel slope
u	mean velocity
u_*	shear velocity $\sqrt{\tau_o/\rho}$
u'_*	shear velocity due to grain roughness
uS	unit stream power
uS/ω	dimensionless unit steam power
X_i	computed sedimentation
Y_i	measured sedimentation
$\overline{X}$	average of computed concentration of sediment
$\overline{Y}$	average of measured concentration of sediment

DETAILS OF CANAL DATA

Total No	No of Each Canal	Canal Data	Water Discharge m^3/s	Channel Width w m	Flow Depth h m	Flow Velocity v m/s	Mean Bed Diameter d_s mm	W S Slope S_w m/m	Water Temp °C	Measured Sed Concen C ppm	Bed Form	Source
		1	2	3	4	5	6	7	8	9	10	11
1	1	American Canal	12.59	11 73	1 83	0.59	0.096	0.000063	23	370	5	Simons (1957)
2	2	American Canal	1.56	3.49	0.80	0.56	0.173	0 000253	21	249	4	
3	3	American Canal	1 22	3.19	0.80	0.47	0.229	0 000294	21	406	3	
4	4	American Canal	29 18	22.19	2.53	0.52	0 253	0 000058	22	115	3	
5	5	American Canal	29.40	14.81	2.59	0.77	0 311	0.000120	22	185	3	
6	6	American Canal	4.14	9 33	1.07	0.41	0 318	0.000135	25	254	3	
7	7	American Canal	3.20	3.96	1.32	0.61	0 349	0.000110	26	44	5	
8	8	American Canal	10.47	6.92	1.60	0.95	0 360	0.000114	26	131	5	
9	9	American Canal	6.42	12 56	1 01	0.50	0.446	0.000218	28	100	3	
10	10	American Canal	4.83	10.73	0.89	0.51	0.465	0.000237	26	52	3	
11	11	American Canal	5.01	7.62	0.89	0.74	0.580	0.000330	26	448	4	
12	12	American Canal	5.62	7.59	1.01	0.73	0.715	0.000302	23	123	4	
13	1	India Canal	156.05	56.27	3.39	0.82	0.020	0 000060	20	2,601	0	Chitale (1966)
14	2	India Canal	59 16	25.49	2 44	0 95	0.021	0 000084	20	5,759	0	
15	3	India Canal	153.25	56.02	3.37	0.81	0.024	0 000060	20	2,887	0	
16	4	India Canal	60.72	25.56	2.49	0.95	0 025	0 000084	20	5 182	0	
17	5	India Canal	157.41	56.47	3.35	0.83	0 030	0 000070	20	2,316	0	
18	6	India Canal	68.82	25 77	2.55	1 05	0 031	0 000110	20	3,557	0	
19	7	India Canal	27.67	17 98	2 52	0 61	0 033	0.000070	20	831	0	
20	8	India Canal	68.92	25.68	2.55	1.05	0.033	0.000110	20	3.508	0	
21	9	India Canal	14.11	13 49	1 85	0.57	0.036	0.000080	20	1,894	0	
22	10	India Canal	14.03	14 66	1.72	0.56	0.037	0.000080	20	4,230	0	
23	11	India Canal	27 50	17 89	2.51	0.61	0.039	0.000070	20	822	0	
24	12	India Canal	158.37	56 61	3 35	0.83	0.039	0.000070	20	2,175	0	
25	13	India Canal	2 02	5.34	0.94	0.40	0.042	0.000115	20	1,417	0	
26	14	India Canal	14.81	13 55	1.86	0.59	0.043	0.000080	20	2,467	0	
27	15	India Canal	33.74	20.58	2.38	0.69	0.043	0 000080	20	797	0	
28	16	India Canal	19.45	16.03	2.38	0.51	0.044	0 000088	20	624	0	
29	17	India Canal	3.00	5 78	1 10	0.47	0 046	0 000115	20	3,132	0	
30	18	India Canal	24.59	18.07	2.24	0.61	0 046	0 000120	20	2,517	0	
31	19	India Canal	1.15	4 35	0.67	0 39	0 048	0.000145	20	1,031	0	
32	20	India Canal	19.22	15 95	2.37	0 51	0 048	0.000088	20	512	0	
33	21	India Canal	13.41	10.58	1 97	0.65	0.050	0.000100	20	981	0	
34	22	India Canal	27.89	18.17	2.17	0 71	0.050	0.000112	20	2,601	0	
35	23	India Canal	13.19	10.70	1.94	0.64	0 051	0.000100	20	671	0	
36	24	India Canal	15.87	17.34	1 57	0.58	0.056	0.000120	20	596	0	
37	25	India Canal	242.19	79 10	3 56	0.86	0.057	0.000064	20	1,490	0	
38	26	India Canal	1 29	4 31	0.79	0.38	0.064	0.000165	20	760	0	
39	27	India Canal	30.86	20.57	2.37	0.63	0.064	0.000080	20	918	0	
40	28	India Canal	132.80	51.90	3.29	0.78	0.064	0.000065	20	1,976	0	
41	29	India Canal	131.39	51.51	3.29	0.77	0.066	0.000065	20	1,593	0	
42	30	India Canal	15.84	17.31	1.57	0.58	0.070	0.000120	20	726	0	
43	31	India Canal	166.36	66.54	3.41	0.73	0.080	0 000057	20	1,425	0	
44	32	India Canal	163.72	66.55	3.39	0.73	0.082	0.000057	20	1.519	0	
45	1	Pakistan Canal	158.09	118.87	2.23	0.60	0 083	0.000070	28	369	5	Mahmood et al (1979)
46	2	Pakistan Canal	94.27	88.39	1.46	0.73	0.084	0.000137	28	190	5	
47	3	Pakistan Canal	29.59	35.66	1.68	0.49	0.085	0.000085	31	103	0	
48	4	Pakistan Canal	76.94	69.49	1.83	0.61	0.108	0.000132	27	125	0	
49	5	Pakistan Canal	52.13	35.66	2.29	0.64	0.110	0.000075	32	156	0	
50	6	Pakistan Canal	54.14	35.36	2.26	0.68	0.112	0.000067	21	61	0	
51	7	Pakistan Canal	55.16	35.97	2.23	0.69	0.112	0.000085	22	289	0	
52	8	Pakistan Canal	55.64	35.66	2.35	0.66	0.113	0.000077	28	511	0	
53	9	Pakistan Canal	528.68	123.44	3.72	1.15	0.113	0.000055	23	95	0	
54	10	Pakistan Canal	51.42	35.66	2.32	0.62	0.114	0.000070	23	76	5	
55	11	Pakistan Canal	48.62	35.66	2.32	0.59	0.116	0.000072	23	32	0	
56	12	Pakistan Canal	151.24	90.22	1.89	0.89	0.116	0.000152	29	188	0	
57	13	Pakistan Canal	52.41	35.66	2.53	0.58	0.117	0.000076	28	128	3	
58	14	Pakistan Canal	138.04	70.41	2.41	0.81	0.118	0.000149	26	563	0	

59	15	Pakistan Canal	52.27	35.36	2.26	0.66	0.121	0.000073	23	58	0
60	16	Pakistan Canal	58.33	35.97	2.47	0.66	0.122	0.000087	29	166	0
61	17	Pakistan Canal	51.88	35.36	2.19	0.67	0.123	0.000086	17	422	0
62	18	Pakistan Canal	52.47	35.36	2.29	0.65	0.123	0.000088	24	869	5
63	19	Pakistan Canal	54.74	35.66	2.19	0.70	0.124	0.000089	16	560	0
64	20	Pakistan Canal	130.46	70.41	2.35	0.79	0.125	0.000129	25	297	0
65	21	Pakistan Canal	140.14	70.10	2.35	0.85	0.126	0.000134	28	564	0
66	22	Pakistan Canal	61.73	35.66	2.53	0.68	0.127	0.000074	29	79	0
67	23	Pakistan Canal	27.50	86.26	0.91	0.35	0.128	0.000142	18	15	0
68	24	Pakistan Canal	50.60	35.66	2.23	0.64	0.128	0.000074	24	54	5
69	25	Pakistan Canal	54.37	35.36	2.19	0.70	0.129	0.000085	18	367	0
70	26	Pakistan Canal	96.59	86.56	1.62	0.69	0.131	0.000139	26	331	0
71	27	Pakistan Canal	52.92	35.36	2.16	0.69	0.132	0.000085	18	153	0
72	28	Pakistan Canal	137.82	69.19	2.38	0.84	0.132	0.000133	28	607	0
73	29	Pakistan Canal	136.32	127.41	1.77	0.61	0.133	0.000086	28	34	0
74	30	Pakistan Canal	51.90	35.66	2.19	0.66	0.136	0.000086	18	386	0
75	31	Pakistan Canal	56.29	35.97	2.29	0.68	0.138	0.000076	24	184	0
76	32	Pakistan Canal	52.13	49.07	1.43	0.74	0.140	0.000148	31	445	0
77	33	Pakistan Canal	70.40	46.63	2.16	0.70	0.142	0.000101	25	346	0
78	34	Pakistan Canal	74.11	46.63	2.23	0.71	0.142	0.000116	32	233	0
79	35	Pakistan Canal	79.17	46.94	2.44	0.69	0.142	0.000095	21	383	0
80	36	Pakistan Canal	70.42	46.63	2.19	0.69	0.143	0.000115	30	82	0
81	37	Pakistan Canal	56.80	46.33	1.92	0.64	0.144	0.000109	30	225	0
82	38	Pakistan Canal	70.40	46.63	2.32	0.65	0.144	0.000116	29	323	3
83	39	Pakistan Canal	153.82	71.63	2.35	0.91	0.144	0.000166	26	584	3
84	40	Pakistan Canal	73.60	46.63	2.26	0.70	0.145	0.000111	31	335	0
85	41	Pakistan Canal	70.71	46.63	2.16	0.70	0.146	0.000099	25	366	3
86	42	Pakistan Canal	74.30	94.79	1.49	0.52	0.146	0.000142	26	77	0
87	43	Pakistan Canal	49.64	46.63	1.68	0.63	0.147	0.000110	30	36	0
88	44	Pakistan Canal	67.71	46.63	2.16	0.67	0.147	0.000110	36	372	0
89	45	Pakistan Canal	77.28	46.63	2.26	0.73	0.147	0.000109	31	577	0
90	46	Pakistan Canal	97.44	70.41	2.10	0.66	0.147	0.000134	26	164	0
91	47	Pakistan Canal	71.92	46.63	2.32	0.67	0.148	0.000112	28	796	0
92	48	Pakistan Canal	75.86	46.63	2.32	0.70	0.148	0.000115	31	351	0
93	49	Pakistan Canal	90.53	88.39	1.52	0.67	0.148	0.000137	28	183	0
94	50	Pakistan Canal	68.13	46.03	2.07	0.71	0.149	0.000127	21	529	3
95	51	Pakistan Canal	77.11	46.33	2.26	0.74	0.149	0.000108	31	289	0
96	52	Pakistan Canal	78.55	46.63	2.32	0.73	0.149	0.000107	32	385	3
97	53	Pakistan Canal	139.74	71.93	2.23	0.87	0.149	0.000107	25	391	0
98	54	Pakistan Canal	72.66	46.63	2.32	0.67	0.150	0.000116	25	142	0
99	55	Pakistan Canal	65.92	46.63	2.16	0.65	0.151	0.000107	25	290	3
100	56	Pakistan Canal	29.48	93.27	0.76	0.41	0.152	0.000088	17	16	0
101	57	Pakistan Canal	67.11	46.94	2.13	0.67	0.152	0.000112	30	54	0
102	58	Pakistan Canal	68.84	47.85	2.19	0.66	0.152	0.000148	15	410	3
103	59	Pakistan Canal	74.84	46.63	2.29	0.70	0.152	0.000107	28	304	0
104	60	Pakistan Canal	70.03	47.24	2.16	0.68	0.153	0.000116	30	48	3
105	61	Pakistan Canal	28.77	85.65	0.91	0.37	0.154	0.000124	18	13	0
106	62	Pakistan Canal	92.79	100.89	1.40	0.66	0.154	0.000106	27	106	4
107	63	Pakistan Canal	297.16	128.32	2.56	0.90	0.154	0.000097	25	2,083	0
108	64	Pakistan Canal	68.78	47.24	2.23	0.65	0.155	0.000147	16	845	3
109	65	Pakistan Canal	74.22	46.63	2.29	0.70	0.155	0.000114	28	333	0
110	66	Pakistan Canal	63.77	47.55	2.16	0.62	0.156	0.000150	16	110	0
111	67	Pakistan Canal	72.66	46.63	2.35	0.66	0.156	0.000112	29	310	0
112	68	Pakistan Canal	391.06	92.05	3.66	1.16	0.157	0.000150	30	342	0
113	69	Pakistan Canal	67.85	46.63	2.13	0.68	0.159	0.000124	25	146	0
114	70	Pakistan Canal	75.32	46.33	2.29	0.71	0.161	0.000104	28	240	0
115	71	Pakistan Canal	156.48	72.24	2.41	0.90	0.161	0.000149	27	228	4
116	72	Pakistan Canal	169.08	72.24	2.47	0.95	0.162	0.000121	28	169	0
117	73	Pakistan Canal	69.18	46.94	2.16	0.68	0.164	0.000102	25	262	0
118	74	Pakistan Canal	85.29	88.39	1.46	0.66	0.164	0.000129	26	132	0
119	75	Pakistan Canal	169.67	70.71	1.89	1.27	0.164	0.000134	30	872	0
120	76	Pakistan Canal	78.92	99.67	1.34	0.59	0.167	0.000104	26	88	0
121	77	Pakistan Canal	84.02	49.38	2.16	0.79	0.167	0.000146	31	56	3
122	78	Pakistan Canal	98.94	86.56	1.65	0.69	0.167	0.000127	26	232	0
123	79	Pakistan Canal	85.21	47.85	2.10	0.85	0.168	0.000132	21	322	0
124	80	Pakistan Canal	47.83	46.33	1.80	0.57	0.169	0.000108	32	215	0
125	81	Pakistan Canal	321.51	119.79	3.41	0.79	0.169	0.000088	14	138	0
126	82	Pakistan Canal	86.34	49.38	2.16	0.81	0.170	0.000147	29	1,007	0
127	83	Pakistan Canal	412.04	111.86	3.63	1.02	0.170	0.000119	25	216	0
128	84	Pakistan Canal	90.42	49.38	2.13	0.86	0.173	0.000153	21	517	0
129	85	Pakistan Canal	183.83	91.14	2.19	0.92	0.173	0.000138	26	373	0
130	86	Pakistan Canal	153.31	70.71	2.10	1.03	0.174	0.000135	30	419	4

131	87	Pakistan Canal	87.50	49.38	2.19	0.81	0.176	0.000144	32	328	0	
132	88	Pakistan Canal	291.27	128.63	2.59	0.87	0.176	0.000100	23	115	0	
133	89	Pakistan Canal	44.00	48.77	1.34	0.67	0.177	0.000145	31	94	0	
134	90	Pakistan Canal	80.19	49.07	2.04	0.80	0.178	0.000148	25	69	3	
135	91	Pakistan Canal	83.31	49.07	2.07	0.82	0.179	0.000145	32	122	0	
136	92	Pakistan Canal	110.72	71.02	2.16	0.72	0.179	0.000137	26	481	0	
137	93	Pakistan Canal	166.87	90.53	1.89	0.98	0.179	0.000113	28	319	0	
138	94	Pakistan Canal	81.52	49.07	2.13	0.78	0.182	0.000152	20	399	0	
139	95	Pakistan Canal	380.58	101.50	2.90	1.29	0.182	0.000105	30	57	0	
140	96	Pakistan Canal	89.48	49.68	2.16	0.83	0.185	0.000154	16	104	0	
141	97	Pakistan Canal	86.25	49.68	2.23	0.78	0.186	0.000154	17	167	3	
142	98	Pakistan Canal	297.41	129.24	2.62	0.88	0.187	0.000098	19	229	0	
143	99	Pakistan Canal	79.60	50.60	2.13	0.74	0.191	0.000154	16	279	0	
144	100	Pakistan Canal	99.48	86.56	1.65	0.70	0.192	0.000129	26	289	0	
145	101	Pakistan Canal	75.69	49.07	2.16	0.71	0.193	0.000148	34	98	0	
146	102	Pakistan Canal	68.92	124.97	1.46	0.38	0.195	0.000045	19	5	0	
147	103	Pakistan Canal	224.44	120.70	2.50	0.74	0.195	0.000082	31	65	0	
148	104	Pakistan Canal	404.62	114.30	3.57	0.99	0.197	0.000119	14	614	0	
149	105	Pakistan Canal	146.62	126.49	1.71	0.68	0.198	0.000087	30	48	0	
150	106	Pakistan Canal	486.82	123.44	4.27	0.92	0.199	0.000103	29	205	3	
151	107	Pakistan Canal	357.76	111.25	3.54	0.91	0.201	0.000125	15	162	0	
152	108	Pakistan Canal	417.42	112.47	3.66	1.01	0.202	0.000117	25	114	0	
153	109	Pakistan Canal	451.40	121.92	4.24	0.87	0.202	0.000098	27	67	0	
154	110	Pakistan Canal	349.97	112.17	3.47	0.90	0.205	0.000112	13	106	0	
155	111	Pakistan Canal	233.10	140.21	2.07	0.80	0.206	0.000098	12	268	5	
156	112	Pakistan Canal	86.54	49.68	2.16	0.80	0.207	0.000154	17	71	3	
157	113	Pakistan Canal	441.29	120.40	4.08	0.90	0.208	0.000093	23	181	0	
158	114	Pakistan Canal	428.15	114.00	3.69	1.02	0.210	0.000122	13	54	0	
159	115	Pakistan Canal	71.30	46.63	2.10	0.73	0.211	0.000104	24	79	3	
160	116	Pakistan Canal	414.47	111.56	3.69	1.01	0.214	0.000121	23	86	0	
161	117	Pakistan Canal	412.72	118.26	3.60	0.97	0.220	0.000121	21	57	0	
162	118	Pakistan Canal	395.13	113.08	3.81	0.92	0.222	0.000061	27	89	0	
163	119	Pakistan Canal	179.56	124.36	2.04	0.71	0.223	0.000112	21	52	0	
164	120	Pakistan Canal	222.09	128.02	2.26	0.77	0.226	0.000104	12	97	0	
165	121	Pakistan Canal	349.46	111.56	3.41	0.92	0.230	0.000121	15	44	3	
166	122	Pakistan Canal	412.29	118.26	3.63	0.96	0.233	0.000120	23	106	0	
167	123	Pakistan Canal	371.80	113.39	3.51	0.94	0.234	0.000120	15	493	0	
168	124	Pakistan Canal	110.12	125.58	1.86	0.47	0.241	0.000086	17	19	0	
169	125	Pakistan Canal	393.21	111.86	3.57	0.99	0.242	0.000121	24	108	0	
170	126	Pakistan Canal	342.95	110.95	3.29	0.94	0.250	0.000119	16	33	0	
171	127	Pakistan Canal	346.71	110.64	3.32	0.94	0.252	0.000123	14	71	0	
172	128	Pakistan Canal	423.25	118.26	3.63	0.99	0.258	0.000121	24	59	4	
173	129	Pakistan Canal	363.33	128.02	2.77	1.02	0.260	0.000093	26	265	0	
174	130	Pakistan Canal	375.65	125.88	3.81	0.78	0.268	0.000116	-1	17	0	
175	131	Pakistan Canal	362.91	120.09	3.57	0.85	0.272	0.000112	14	116	0	
176	132	Pakistan Canal	207.62	126.19	2.16	0.76	0.273	0.000099	14	49	0	
177	133	Pakistan Canal	363.64	110.95	3.44	0.95	0.275	0.000120	16	103	0	
178	134	Pakistan Canal	392.70	119.79	3.57	0.92	0.275	0.000112	14	94	0	
179	135	Pakistan Canal	387.69	122.23	3.72	0.85	0.279	0.000107	15	32	0	
180	136	Pakistan Canal	394.77	117.65	3.54	0.95	0.279	0.000113	16	44	0	
181	137	Pakistan Canal	337.28	116.43	3.20	0.91	0.289	0.000112	14	39	0	
182	138	Pakistan Canal	279.80	135.94	2.32	0.89	0.293	0.000112	28	123	4	
183	139	Pakistan Canal	355.72	116.74	3.26	0.93	0.299	0.000109	14	42	3	
184	140	Pakistan Canal	267.65	117.35	2.80	0.81	0.313	0.000112	18	65	3	
185	141	Pakistan Canal	388.05	121.92	3.66	0.87	0.331	0.000108	-1	18	0	
186	142	Pakistan Canal	481.92	123.44	4.30	0.91	0.364	0.000079	18	29	0	
187	1	Rio Grande Conveyance Canal	36.51	27.43	0.89	1.50	0.180	0.000520	17	985	5	Culbertson et al. (1972)
188	2	Rio Grande Conveyance Canal	35.38	22.56	1.10	1.43	0.180	0.000660	4	2,486	5	
189	3	Rio Grande Conveyance Canal	35.38	22.56	1.11	1.42	0.180	0.000590	3	3,049	5	
190	4	Rio Grande Conveyance Canal	33.68	22.56	0.89	1.67	0.200	0.000730	17	1,348	4	
191	5	Rio Grande Conveyance Canal	25.19	22.86	1.50	0.74	0.210	0.000650	15	906	3	
192	6	Rio Grande Conveyance Canal	36.22	21.34	1.02	1.66	0.210	0.001110	18	2,475	4	
193	7	Rio Grande Conveyance Canal	25.19	20.12	1.25	1.00	0.230	0.000650	15	906	3	
194	8	Rio Grande Conveyance Canal	25.75	21.34	1.30	0.93	0.270	0.000650	15	1,025	3	
195	9	Rio Grande Conveyance Canal	25.75	22.86	1.37	0.82	0.280	0.000650	15	1,025	3	

196	1	Canal del Dique	421.00	135.00	3.82	0.82	0.210	0.000057	30	626	0	Nedeco (1973)
197	2	Canal del Dique	567.00	140.00	4.60	0.88	0.210	0.000071	30	590.8	0	
198	3	Canal del Dique	478.00	120.00	3.55	1.12	0.210	0.000062	30	266.6	0	
199	4	Canal del Dique	83.00	108.00	2.47	0.31	0.210	0.000026	30	11.2	0	
200	5	Canal del Dique	158.00	114.00	2.65	0.52	0.210	0.000036	30	120.7	0	
201	6	Canal del Dique	440.00	85.00	4.47	1.16	0.150	0.000059	30	232.7	0	
202	7	Canal del Dique	544.00	84.00	5.13	1.26	0.150	0.000089	30	156.5	0	
203	8	Canal del Dique	120.00	76.00	3.54	0.45	0.150	0.000020	30	10.2	0	
204	9	Canal del Dique	111.00	41.00	4.12	0.66	0.100	0.000091	30	163.5	0	
205	10	Canal del Dique	142.00	36.00	3.92	1.01	0.100	0.000068	30	393.2	0	
206	11	Canal del Dique	55.00	39.00	3.08	0.46	0.100	0.000089	30	23	0	
207	12	Canal del Dique	57.00	31.00	3.42	0.54	0.100	0.000020	30	5.9	0	
208	13	Canal del Dique	322.00	69.00	3.78	1.23	0.120	0.000091	30	328.8	0	
209	14	Canal del Dique	280.00	85.00	3.15	1.05	0.120	0.000077	30	192.8	0	
210	15	Canal del Dique	370.00	88.00	3.91	1.08	0.120	0.000089	30	140.9	0	
211	16	Canal del Dique	68.00	74.00	2.16	0.43	0.120	0.000020	30	9.3	0	
212	17	Canal del Dique	89.00	32.00	2.68	1.04	0.185	0.000170	30	205.4	0	
213	18	Canal del Dique	126.00	34.00	2.62	1.41	0.185	0.000150	30	151.6	0	
214	19	Canal del Dique	80.00	30.00	2.57	1.04	0.185	0.000170	30	261.3	0	
215	20	Canal del Dique	29.00	27.00	2.21	0.49	0.185	0.000020	30	8.3	0	
216	21	Canal del Dique	169.00	95.00	2.21	0.80	0.120	0.000051	30	163	0	
217	22	Canal del Dique	228.00	90.00	2.78	0.91	0.120	0.000041	30	168.7	0	
218	23	Canal del Dique	215.00	100.00	2.93	0.73	0.120	0.000047	30	222.3	0	
219	24	Canal del Dique	51.00	93.00	1.80	0.30	0.120	0.000010	30	2.9	0	
220	25	Canal del Dique	225.00	86.00	2.93	0.89	0.125	0.000041	30	215.8	0	
221	26	Canal del Dique	38.00	77.00	2.49	0.20	0.125	0.000003	30	16.7	0	
222	27	Canal del Dique	150.00	45.00	2.62	1.27	0.125	0.000142	30	215.9	0	
223	28	Canal del Dique	128.00	35.00	2.96	1.24	0.125	0.000129	30	58.3	0	
224	29	Canal del Dique	153.00	41.00	2.63	1.42	0.125	0.000177	30	124.1	0	
225	30	Canal del Dique	82.00	75.00	2.08	0.53	0.125	0.000024	30	148.4	0	
226	31	Canal del Dique	95.00	75.00	1.87	0.68	0.125	0.000046	30	118.9	0	
227	32	Canal del Dique	81.00	78.00	1.82	0.57	0.125	0.000035	30	89.2	0	
228	1	West Pakistan (CHOP) Canal	172.44	112.78	1.31	1.17	0.090	0.000194	16	232	0	Chaudry et al. (1970)
229	2	West Pakistan (CHOP) Canal	120.91	55.47	2.44	0.89	0.100	0.000200	20	181	0	
230	3	West Pakistan (CHOP) Canal	109.58	57.91	2.68	0.71	0.110	0.000080	24	146	0	
231	4	West Pakistan (CHOP) Canal	233.61	118.26	2.47	0.80	0.110	0.000214	15	148	0	
232	5	West Pakistan (CHOP) Canal	146.68	67.67	2.68	0.81	0.120	0.000232	24	473	0	
233	6	West Pakistan (CHOP) Canal	359.61	111.25	2.10	1.54	0.120	0.000116	23	531	0	
234	7	West Pakistan (CHOP) Canal	362.44	99.06	3.08	1.19	0.120	0.000118	29	464	0	
235	8	West Pakistan (CHOP) Canal	351.12	112.17	2.13	1.47	0.130	0.000124	18	706	0	
236	9	West Pakistan (CHOP) Canal	424.74	111.86	2.38	1.60	0.140	0.000155	19	1,153	0	
237	10	West Pakistan (CHOP) Canal	166.75	67.67	2.56	0.96	0.190	0.000051	27	116	0	
238	11	West Pakistan (CHOP) Canal	27.52	23.77	1.68	0.69	0.200	0.000086	29	286	0	
239	12	West Pakistan (CHOP) Canal	112.41	57.30	2.32	0.85	0.200	0.000134	24	595	0	
240	13	West Pakistan (CHOP) Canal	322.80	120.40	2.68	1.00	0.200	0.000196	22	526	0	
241	14	West Pakistan (CHOP) Canal	362.44	118.26	2.99	1.03	0.200	0.000161	18	663	0	
242	15	West Pakistan (CHOP) Canal	393.59	99.67	3.38	1.17	0.200	0.000181	17	299	0	
243	16	West Pakistan (CHOP) Canal	413.41	110.64	2.44	1.53	0.200	0.000115	18	1,297	0	
244	17	West Pakistan (CHOP) Canal	209.26	71.63	3.32	0.88	0.210	0.000127	22	484	0	
245	18	West Pakistan (CHOP) Canal	328.47	97.54	3.32	1.01	0.210	0.000188	19	432	0	
246	19	West Pakistan (CHOP) Canal	334.13	110.34	2.47	1.23	0.210	0.000159	20	428	0	
247	20	West Pakistan (CHOP) Canal	342.62	116.74	3.11	0.94	0.210	0.000254	22	620	0	
248	21	West Pakistan (CHOP) Canal	376.60	115.82	2.35	1.39	0.210	0.000141	21	702	0	

249	22	West Pakistan (CHOP) Canal	427.57	121.62	3.17	1.11	0.210	0.000202	16	1,217	0
250	23	West Pakistan (CHOP) Canal	146.11	55.78	2.62	1.00	0.290	0.000182	27	244	0
251	24	West Pakistan (CHOP) Canal	153.47	58.52	2.71	0.97	0.290	0.000165	24	261	0
252	25	West Pakistan (CHOP) Canal	255.41	112.17	2.56	0.89	0.290	0.000207	12	305	0
253	26	West Pakistan (CHOP) Canal	114.96	57.91	2.35	0.85	0.300	0.000140	17	236	0
254	27	West Pakistan (CHOP) Canal	122.04	53.65	2.38	0.96	0.300	0.000185	11	302	0
255	28	West Pakistan (CHOP) Canal	138.47	66.14	2.29	0.92	0.300	0.000165	15	395	0
256	29	West Pakistan (CHOP) Canal	138.47	59.44	2.38	0.98	0.300	0.000179	11	150	0
257	30	West Pakistan (CHOP) Canal	143.85	63.40	2.47	0.92	0.300	0.000238	23	197	0
258	31	West Pakistan (CHOP) Canal	139.03	57.91	2.44	0.98	0.311	0.000176	22	198	0
259	32	West Pakistan (CHOP) Canal	226.53	109.42	2.29	0.91	0.311	0.000185	19	388	0
260	33	West Pakistan (CHOP) Canal	399.26	112.78	3.41	1.04	0.311	0.000178	17	1,317	0

Note for bed form:

0 Not observed
1 Plane bed without sed. movement
2 Ripples
3 Dunes
4 Transition
5 Plane bed with sediment movement
6 Standing waves
7 Anti dunes
8 Chute - pools

EVALUATION OF MULTI-PURPOSE UTILIZATION POSSIBILITIES OF UPDATED DRAINAGE STRUCTURES

Kulhavy Frantisek [1] Kulhavy Zbynek [2]

ABSTRACT

This paper comments on an original methodology, developed by the authors, of analysing the adaptability of existing drainage systems and structures to changed conditions. The method is based on a modified ecological index, a parameter characterising the site conditions in a summary way and based on the currently available data on climate, hydrogeology, soils, geomorphology and production. The analysis of the actual state of a drainage system starts with a detailed review of its design parameters, a reconnaissance of its actual state (the quality of materials used, the degree of corrosion, siltation or other type of deterioration, etc.). Then, it must be stated how well the system and its parts have been achieving the objectives for which they were designed and built.

The analyses outlined above then become a basis for designing several alternative technical ways of modernisation, each capable of fulfilling the required environmental and economic targets.

As much self-controlling and automation as possible is recommended, but an economically sustainable monitoring may often be necessary in order to check how a modernised drainage system fulfills its functions. Moreover, large systems may require an active human control, especially in extreme situations such as floods or severe droughts.

INTRODUCTION

One of the side effects of deep socio-economic changes which have been occurring in the Czech Republic over last the decade was that most of the existing land drainage structures and systems, covering as much as 29% of the country's agricultural land, were neglected. If this trend continues, then both the fertility of

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soils and the ecological stability of affected regions will be put on risk. Hence, the settlement of ownership rights in relation to drainage systems and other components of the landscape is urgently needed. Moreover, concepts and approaches have to be elaborated allowing optimization of water regime and environmental conditions in a landscape exploited by agriculture and forestry.

One of the results of the ongoing changes of land ownership, tenancy and exploitation is that the requirements on existing drainage systems also are and will be changing. The parameters (of these systems) presently required are different from those for which the systems were designed and built, as well as different from those which these systems, after a decade of neglect, actually possess. This discrepancy can only be solved if the drainage systems in question are properly modernised. A formidable task for a consulting engineer is then to analyse the site conditions and the actual state of existing drainage systems and structures and to suggest to the user an optimum way of their modernisation that would be both technically possible and environmentally acceptable and, at the same time, would lead to the required economic effect.

The prospective target of harmonising our activities in the landscape approaching the present European Union principles („EU Directive For Water Supplies Management Planning") is a complete coordination of the water supply management policy including the landscape protection understood from the viewpoint of its permanently maintained development.

In our location conditions (*KULHAVY,F. – SVIHLA, VL. 1997*), almost all exploitable water resources are the result of various forms of precipitation water accumulation in the landscape. From this viewpoint, the agricultural and forest soils are potentially significant control elements of the catchment area water regime. It can be therefore stated that the environmental policy level may influence the quality as well as the volume of water resources thus improving the hydrological balance in the given catchment area. For this reason, a solution of water supply management in close connection with the landscape protection and forming is highly desirable. In the practice, this means a full coordination of the regional and local territorial environment stability system solutions as well as that of the consequential complex land improvement projects, the revitalising of the river systems and the modernising and restructuralizing of hydromelioration structures together with an effective control of anthropogenous activities performed in the landscape. From the environmental point of view, the enhanced water retention in the catchment area and thus a positive influencing of transport processes are emphasised for the landscape melioration works. The balance of these processes can be substantially improved by larger areas of biologically unaffected forest and meadow complexes placed in the upper (infiltration) parts of the catchment area.

In these areas, the economic functions must always be overridden by the non-production (i.e. water and soil protecting) ones.

CONCEPTION OF THE PROPOSED TECHNICAL SOLUTION

At present, new property and legal conditions together with the economic ones must be considered for the utilisation of hydromelioration structures accepting their presence in the cultural landscape so that differentiated judgement aimed on achieving of required environmental and economic effects will be applied to the possibilities of the optimum utilisation thereof in each of the localities. Optimised construction, restructuralizing and modernising interventions into the building processes respecting at the same time the multi-purpose utilisation of these structures (i.e. achieving of their required ecological aspects) based on a detailed analysis of the location, ecological and economic relations will have to be designed. The utilisation possibilities of the following melioration measures will be considered when designing new technical, biological and organisational measures aimed on enhanced effect of the existing draining structures:

Erosion Soil Protection

Due to the erosion soil protection, retarded water runoff from the catchment area as well as a decrease in the transport process volume of soil particles released by the erosion can be achieved due to the increase in the infiltration potential and to the surface water runoff control.

Melioration Measures

With the exception of the polluted soil reclaiming and certain chemical soil treatment procedures, the melioration measures always contribute to the water-and-air soil regime enhancement, to controlled surface water infiltration into the subsoil, to an increase in the soil retention ability and in the transport of nutrients and other useful substances in the soil and, finally, support an increase in the ecological landscape stability together with an improvement in the hydrological catchment area relations (during the vegetation period, these steps may cause not only an increase in the accumulated water quantity in the soil by 500 up to 1,500 m^3ha^{-1}, but also a permeability enhancement of extremely impervious soils by more than 4 times.)

Biological Drainage

From the ecological point of view, it is advantageous to add biological measures (e.g. meadow growths creating the desired „filtering capacity“ in addition to the landscape creating function by their large leaf surface areas) and the biologic-and-technical ones (e.g. the use of vegetation earmarked by a high evapotranspiration ability such as poplars, willows, alders, birches, sunflowers or using properly selected sowing procedures) to the structural-and-technical interventions. It will be reasonable to restore the function of some opened drainage channels within the framework of the landscape revitalising because, in addition to their biologic corridor functions, they may cause a significant decrease in the costs connected with their functioning and maintenance due to their multi-purpose utilisation (e.g. a small check gate can be used to retard the drainage water runoff in the spring season etc.) thus contributing among others to a decrease in the water and wind erosion intensity.

Controlled Drainage Systems

From the environmental point of view, the controlled drainage systems represent significant landscape stabilising elements keeping the soil moisture at levels near to the optimum values required by the given plant thus increasing the soil resistance against wind and water erosion. The possibility of retarding 500 up to 2,500 and even more m^3ha^{-1} water during the vegetation period (*KULHAVY,F. 1992*) is a proof that these measures are a suitable supplement to the revitalising of water streams and a highly desirable area measure (see ***Fig. 1***) from the viewpoint of the hydrological catchment area balance. The possibility of transforming surface runoffs to retarded ones of soil water may represent a significant contribution to the optimising of the hydrological balance in small catchment areas as a replacement for the „dry intercepting ponds“ and retention reservoirs; under suitable conditions, closed water (and nutrients !) circulation systems may be designed using this way as well. The following controllable drainage systems are classified in this group (*SOUKUP,M. - KULHAVY,Z. 1997*):

- water level control in an open ditch network;
- a flooded intercepting drain with water repumping into a recipient;
- drainage provided with a controlled runoff;
- areal retardation drainage;
- controlled drainage with various degrees of automation and irrigation water dependability;
- drainage water transfer for irrigation and infiltration;
- pulsed irrigation drainage;
- water level control of spring pits;
- utilisation the drainage and surface water with a sufficient quality degree to increase the underground water resources.

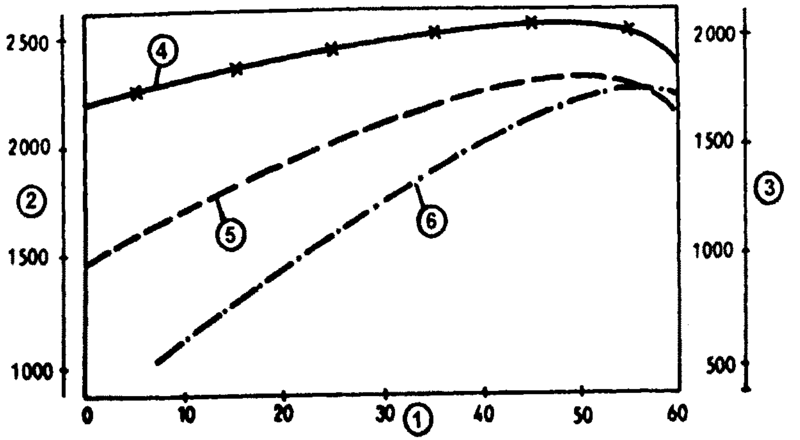

Fig. 1 - Retention soil abilities with a drainage embedding depth of 1.10 m

1 - contents of the first category grain volume percentage (by Kopecky)
2 - water retention capacity of the soil [$m^3.ha^{-1}$] by variant 4 a 5
3 - water retention capacity of the soil [$m^3.ha^{-1}$] by variant 6
4 - by groundwater table 0,40 [*m*]
5 - by groundwater table 0,60 [*m*]
6 - by groundwater table 1,00 [*m*]

Irrigation Structures

The irrigation structures act as production-and-stabilising elements in landscapes with adverse location (above all climatic and hydrological) conditions. In localities where they have been built together with drainage systems, it is worth consideration whether the use of a control drainage with water supply from an irrigation system (e.g. using a pulsed irrigation drainage) is or is not more advantageous from the technical and economical point of view. The essential rationalisation step is not only a purposeful reduction of water consumption per agricultural production unit but also utilisation of non-traditional water resources such as waste water, dung-water, sewage sludge etc. The performance effect is conditioned by a multi-purpose and qualified utilisation of the particular structure as a whole.

Water Stream Adjustment And Revitalising.

The water stream adjustment and revitalising are elements exerting an essential influence not only on the hydrological balance elements (*SOUKUP M. 1998*) but also on the ecological landscape stability. For this reason, all proposed measures used within the framework of the landscape planning should be carefully considered.

With existing melioration piping channels (*SOUKUP ET ALL. 1998*), their contribution and imperfections should be carefully compared in the given economic and ecological conditions; this comparison should be followed by a decision whether these channels are to be saved, discarded or modernised.

Construction Of Ponds And Low-Volume Water Reservoirs

The ponds and small water reservoirs are integral parts of our cultural landscape supporting significantly the environment protection as well as the optimising of the water supplies management balance in the given catchment area. The water reservoirs may perform protection, equalising, accumulation, reclaiming, retaining, infiltration, cleaning, esthetic, leisure and hygienic functions. The low-volume water reservoirs contribute significantly to the water quality improvement (pollution removal using self-purification processes) being at the same time irreplaceable as basic water supplies in areas with poor hydrographic network densities.

Torrent Control and Forest Reclamation

The stop logs built in torrents are significant components of the cultural landscape protection solution in water stream spring areas.

Design Of Landscape Vegetation Arrangements

At present, the design of the landscape vegetation arrangements should become an integral part of all melioration and revitalising steps taken in the landscape, in particular for their biologic-and-technical, ecological and esthetic functions performed at the same time.

METHOD OF OPTIMUM TECHNICAL DRAINING STRUCTURE SOLUTION EVALUATION

Whenever trying to find the best possible technical solution of a modernised draining structure, the designer's considerations should be based on the principle that the protection of the ecological system and its biological diversity are essential for maintaining and restoring the natural hydrological cycle. For this reason, the most important precondition for determining the draining structure adaptability to varying operational and environmental conditions is a detailed analysis of the location relations and, in particular, of the following area of interest characteristics:

- data concerning the structure location including the proprietary and legal relations as well as its integration into the surrounding landscape;
- information concerning the geomorphological conditions, in particular those related to the terrain inclination and exposition;
- information concerning the geological and hydrogeological area of interest (the partial catchment area) conditions and, in the best possible case, concerning all the higher-category catchment area data;
- data concerning the hydropedological conditions;
- data concerning the climatic conditions, in particular those concerning the precipitation volume, temperatures and air humidity including the wind conditions, the degree of evaporation etc. for information as well;
- hydrological area of interest data as well as those of the partial catchment area; more generally, the district data (i.e. those of the adjacent catchment areas) may be included as well;
- data concerning the biogeographical structure including the planned area of interest utilisation or, possibly, planned anthropogenous activities in the partial catchment area;
- the construction Project documentation in its optimum complexity; if such a documentation is not available, it is necessary to ascertain the essential structure parameters, their actual technical condition and, above all, to inventarize all performance objects within the framework of a separate investigation;
- data concerning the economic possibilities of the Investor together with possible connections to the financial support resources etc.

Based on the detailed analysis of the above mentioned area of interest characteristics, the area of interest should be now divided into individual coherent location districts (using the climatic or hydropedologic criteria or in accordance with draining groups and with the planned area utilisation) proceeding their evaluation as specified by the subsequently described method; as its primary criterion, this method utilises the value of the „Ecological Index EI" (*KULHAVY F. 1981, 1983, 1992*) characterising the location conditions during the vegetation period (April through September) for the planned area of interest utilisation.

The Calculation for the coherent location districts itself should be performed using the following equations:

$$EI = SI - 0{,}05\ (V_c - 350)$$

where V_c is the average moisture requirement of the crop or cropping procedure over the whole vegetation season in *mm*,

$$SI = KI + B + C - D$$

where SI is the site index for the observed period.
C is allowance for soil water (***Fig.2***).
B is the soil number dependent on soil grain size (***Fig.3***), (in formula *[2]*)
KI is the climatic index whose magnitude is calculated according to equations *[6]* and *[7]* in dependence on the value of potential evapotranspiration of field cultures S^+ given by the formula:

$$S^+ = S - K - n\,.\,s$$

where S is total precipitation over the observed period in *mm*,
K is the allowance for atmospheric moisture in *mm* given by the formula:

$$K = 0{,}0133\,.\,n\,.\,(80 - a)$$

where n = 183, is the number of days in vegetation period,
a is the average relative atmospheric moisture in per cent,
s is specific precipitation in the area of field cultures in $mm.d^{-1}$ given by formula:

$$s = 0{,}0822\,.\,e\,.\,t + 0{,}5753$$

where e is exposure coefficient whose values for Czech Republic are at ***Tab.1***,
t is the average atmospheric temperature over the observed period in °C

Tab.1 Exposure coefficient „*e*“

exposure	Inclination of the terrain up to %		
	9	17	27
South	1,04	1,09	1,12
SE-SW	1,05	1,09	1,12
E-W	1,04	1,07	1,09
NE-NW	1,02	1,02	1,02
North	1,00	0,99	0,96

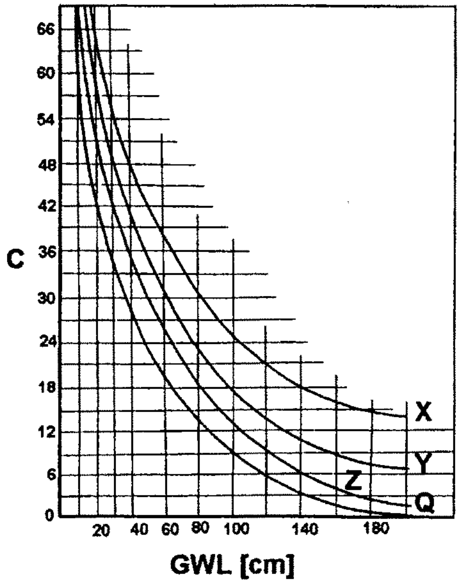

Fig. 2 - Parameter „*C*“ depending on the 1st category grain percentage (by Kopecky)

X ≥ 60% Y = 30% to 60%
Z = 20% to 30% Q < 20%
GWL – Groundwater level [*cm*]

$$\text{For } S^+ > 0 \qquad KI = \frac{365}{n} \cdot \frac{S^+}{e\,.\,t}$$

$$\text{For } S^+ < 0 \qquad KI = \frac{3{,}65}{n} \cdot e\,.\,t\,.\,S^+$$

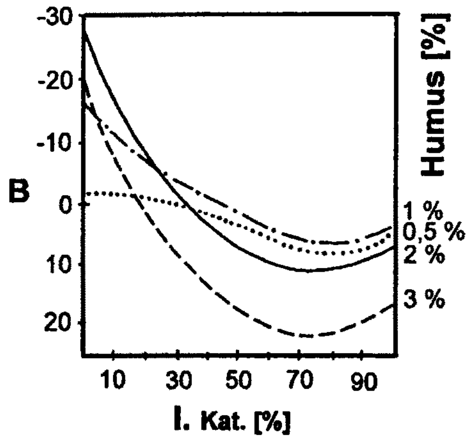

Fig. 3 - Determining the soil number „*B*“ depending on the 1st category grain and humus contents

D is reduction for inclination of terrain given by formula:

$$D = k\,.\,J$$

where k is the coefficient of dependence on grain size, values are at ***Tab.2***
J is the inclination of the terrain in per cent.

Tab.2 Coefficient „*k*“

I.kat. %	<10	10-20	20-30	30-45	45-60	60-75	>75
k	0,20	0,35	0,50	0,70	0,90	1,25	1,50

The effect of the projects operating parameters on attaining optimal growth environment for crops is expressed by the so-called operation index:

$$PI = d \cdot b + c \qquad [9]$$

where d is characteristics of the size of the serviced area (d=1 for an area of up to 100ha, d=2 for area above 100ha),

b is the characteristic of the water resource (b=1 for an abundant water resource always with drainage, b=1.5 for an average water resource and b=2 for a poor water resource usually accumulation is needed),

c is the characteristics of the technical concept of the project (planned)

$c = 0$ ..... standard drainage
$c = 2$ ..... semiautomatic operation
$c = 3$ ..... fully automated operation

Whenever designing the optimum technical solution enabling a multi-purpose utilisation of the existing drainage structures, the designer should consider the following environmental requirements:

a) optimising the soil humidity conditions during the vegetation period thus creating suitable conditions for biological diversity in the given landscape (*EI*, existence of an irrigation structure);
b) increasing the soil retention capability thus providing a better precipitation water utilisation in the catchment area and creating suitable conditions for a better water runoff balance (*B*);
c) increase the soil infiltration capability together with the porous soil environment conditions, in particular in the water spring areas thus enhancing the water supplies management balance in the given catchment area (C, K_S, existence of an irrigation structure);
d) solving the underground water retention with a possibility of performing the function of swampy ground areas and increasing the minimum flow rates of the surface water in conditions with a poor interest in agricultural soil utilisation and in suitable ecological conditions (*EI, J*);
e) minimising the wind and water erosion intensity (*EI, J,* existence of an irrigation structure).

The technical solution itself should be selected using the following *Table*:

Table 3 - Optimum technical solution derived from the evaluated characteristics

EI from	PI	B	C	J	K_S	Technical solution
0 to 60	< 1	-20 to 0	> 12	≤ 0.2	> 0.4	I.
10 to 60	< 3	-20 to 20	> 6	≤ 0.2	> 0.1	II.
10 to 60	< 5	-20 to 20	> 6	≤ 4.0	> 0.2	III.
30 to –10	< 4	-20 to 10	> 3	≤ 0.1	> 0.1	IV.
40 to –25	< 7	-20 to 10	> 3	≤ 2.0	> 0.2	V.
40 to –25	< 4	-20 to 20	> 9	≤ 3.0	> 0.2	VI.
20 to –40	< 3	-20 to 0	< 9	≤ 2.0	0.5 – 2.3	VII.
40 to –25	< 3	-20 to 20	> 3	≤ 4.0	> 0.1	VIII.
40 to –40	< 3	-20 to 0	< 3	≤ 0.2	> 1.0	IX.
< -28			< 9	< 0.2	< 0.1	X.
> 60			< 6	> 4.0	> 3.0	

K_S – Saturated Hydraulic Conductivity $[m.d^{-1}]$

Marking of the optimum technical solution enabling a multi-purpose utilisation of the existing draining structure:

I. - water level control in an open ditch network where the water level in the ditches or channels is controlled using stop logs; water infiltrates into the soil profile or flows into the draining system connected hereto;

II. - a flooded intercepting drain with water re-pumping into a recipient provided with a possibility of an automatic time and space control of the underground water level (hereinafter referred-to as „UWL“ only);

III. - drainage provided with a controlled runoff (viz *SOUKUP,M. – KULHAVY,Z. 1997*),

IV. - areal retardation drainage (viz *SOUKUP,M. – KULHAVY,Z. 1997*);

V. - controlled drainage with various degrees of automation and irrigation water dependability (viz *KULHAVY,F. 1992*; *SOUKUP,M. – KULHAVY,Z. 1997*);

VI. - drainage water transfer for irrigation and infiltration (viz *SOUKUP,M. – KULHAVY,Z. 1997*);

VII. - pulsed irrigation drainage (periodical irrigation water supply) suitable in localities with pressurised irrigation water and with an impervious drainage subsoil (viz *KULHAVY,F. 1992*);

VIII. - water level control of spring pits (viz *SOUKUP,M. – KULHAVY,Z. 1997*);

IX. - utilisation the drainage and surface water with a sufficient quality degree to increase the underground water resources (viz *KULHAVY,F. 1992*);

X. - The structure modernising is not recommended.

CONCLUSION

The said methods may be used in combination with computer technology for the optimization of the technical solution of the construction (project) not only with regard to economics but also with regard to the living environment. This indicator will first be maximized for the purpose of designing variant installations of project, then groups of installations forming compact ensembles; a section of the most suitable variants of the ensembles will then be made for designing a project having the optimal technical, economic, social and operation parameters.

The use of described methods for chosing optimal technical concepts of hydromelioration projects may improve projects in following respects:

- stabilization of agroecosystem and thereby the protection of the human environment;
- increase the productivity of the agroecosystem to closest approximation to potential yield;
- optimization of water management balance in the serviced area;
- minimization of energy consumption in the construction and operation of the project;
- reduced labour demand and improved working conditions;
- improved nutrient distribution to protect agroecosystems;
- improved conditions for the full utilization of agrotechnology in required time and sequence independent of weather conditions.

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SIMULATION OF DRAINAGE AND REUSE SYSTEM FOR WATERTABLE MANAGEMENT OF CANAL IRRIGATED AREAS A CASE STUDY

Ranvir Kumar[1] Joginder Singh[2]

ABSTRACT

The introduction of canal irrigation in the semi-arid regions of the Haryana State of India underlain with saline ground water in early sixties led to the rise in water levels at an annual rate of 0.3 to 1.0 m and secondary salinization adversely affecting crop production. To develop feasible technologies for the reclamation of such areas, a pilot study on sub-surface tile drainage systems was undertaken in an area at the Haryana Agricultural University Farm having shallow water levels and high salinity. The drains with three spacings (24, 48, 72 m) were placed at a depth of 2.5 m. The water levels, drainage rates and soil salinity data from the study area growing vegetable crops (egg plant, tomato and potato) were used to calibrate the Field Agricultural Irrigation and Drainage Simulation (FAIDS) model for the period 1985-1989 and validate it for the period 1989-93. A number of simulations were also carried out to finalize optimum drain configuration (spacing x depth) under existing agro-hydrological conditions. The drain configurations of 75 m x 2 m (Ist option) and 100 m x 2.5 m (2nd option) performed equally well based on salinity in the root zone and crop performance. In both the options, relative evapotranspiration (ET_a/ET_p) of 0.81 was attained during the third year of operation of the drainage system under normal rainfall conditions. The occurence of a maximum one-day rainfall event (1 in 10 years) during the fifth year resulted in the failure of one out of three crops in both the options in that year indicating the necessity of integration of a surface drainage system with the subsurface drainage under abnormal rainfall events. The existing inland basin

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drainage conditions did not permit the disposal of drainage effluent. The reuse system was therefore, integrated with the drainage system. A model RESBAL was coupled with the calibrated and validated model FAIDS and run for eight years to optimally design a series of connected reservoirs for the disposal of drainage effluent from an area provided with a subsurface drainage system. The possibility of the reuse of the disposed water for irrigation, aqua culture and salt harvesting was also studied comprehensively in order to maintain proper salt balance in the root zone. On the basis of this study, subsurface drainage systems coupled with surface drainage systems are being extended in Haryana to over 2000 ha of the farmers' land severely affected with waterlogging and soil salinity using a tile-laying trenching machine.

INTRODUCTION

Haryana is located in the north-western part of India between latitude 27° 39′ and 30° 55′ N and longitude 74° 28′ and 77° 37′ E with a total land area of 44200 km^2. The state lies on the watershed between the Ganges and the Indus river basins. The Yamuna river which forms the eastern boundary is a tributary to the Ganges and the Ghaggar river which flows along the north-western boundary belongs to the Indus basin. About 80 per cent of the state area is agricultural land and nearly 57 per cent of the cultivated land is irrigated through canal and ground water. The large scale canal irrigation in the south-western part of the state through the Bhakra Irrigation System during the early sixties led to the rise in ground water table in nearly 60 per cent of the area. The areas experiencing the rise in water levels are primarily underlain by brackish and saline ground waters which are not usable for irrigation purposes. Haryana, with its location between the Himalayan mountains on the north-east and the Thar desert on the south-west, is mainly an extensive closed basin (Anonymous, 1986). A topographical depression exists in the centre with its axis passing through Delhi-Rohtak-Hisar and Sirsa on the regional scale and ground water moves towards this depression. The state also forms the water divide between the Indus and the Ganges basins. The climate in the problem areas varies from arid to semi-arid with an annual precipitation of 300-500 mm, most of which is received in the monsoon period (July to September). The losses from the irrigation system through conveyance and water application, unfavourable geo-hydrological conditions and poor ground waters are the major factors contributing to the rise in water levels.

During the last three decades, the water table in the canal irrigated areas has risen at a rate of 30 to 100 cm annually. In nearly 400,000 hectares, the watertable has already come within 3 m of the ground surface, resulting in the degradation of the land resource due to waterlogging and secondary salinization (Anonymous, 1983). According to a study, it is expected that in the next three decades the area under critical water table depth will register a four-fold increase if no curative measures are undertaken.

Therefore, in order to develop feasible drainage and reclamation technologies, studies were undertaken at a pilot scale on the University Farm, Hisar, a part of the inland drainage basin. It is essential to develop suitable simulation models to transfer the results from these studies to other problematic areas. The calibrated and validated model would in turn help in deciding the drain depth and spacing under various cropping, soil and hydrological conditions to maintain a favourable salt and water balance for the proper agricultural production. The present paper primarily deals with the calibration and validation of the Field Agricultural Irrigation and Drainage Simulation Model - FAIDS (Roest, et.al., 1991) by using water levels, drainage discharge and soil salinity data generated from horizontal tile drainage studies at the vegetable farm during the period 1985-1993. The calibrated model was used to simulate number of options to decide the optimum drain spacing and depth under existing agro-hydrological conditions including a once in 10 years 1-day maximum rainfall event which occurred in the fifth year. In view of the absence of a natural outlet, the drainage system should be integrated with the builtin provision for the storage and reuse of the drainage effluent on a long term basis for maintaining a favourable salt-water balance in the area. The model FAIDS in combination with a reservoir balance model has been used to design an integrated reuse system at the Farm.

The Model

The FAIDS model is a simulation model describing water and salt movement in the unsaturated system consisting of effective root and capillary zones and the upper part of the saturated system and simulates for one time step and one crop the irrigation water application, evapotranspiration, drainage and salinity changes

(Roest, et al. 1991). The following fluxes are estimated on a daily basis:

- infiltration of water from the soil surface due to irrigation or rainfall;
- percolation to the water table;
- evapotranspiration from soil and crop;
- capillary rise from the water table into the root zone;
- drainage through a possible sub-surface drainage system;
- seepage/leakage from/into the underlying aquifer.

The overview of the different fluxes as represented in the model are shown in Fig.1

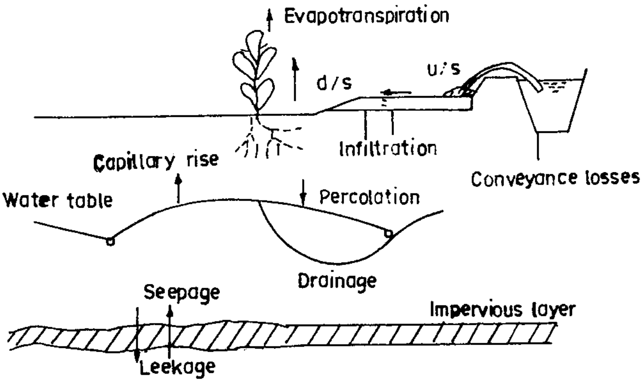

Figure 1. Overview of fluxes considered in the FAIDS model

In the model, two reservoirs for the soil system, namely unsaturated (above water level) and saturated (below water level) are considered and both can be partitioned uniformly into a number of layers (Fig. 2).

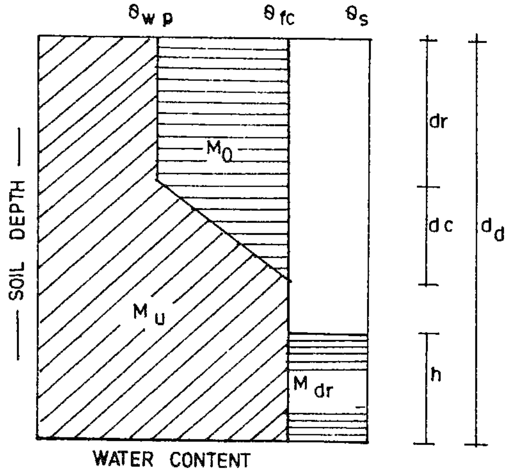

Figure 2. Schematization of soil profile

In the unsaturated reservoir, the maximum quantity of water which can be extracted by plant roots is the amount available between field capacity and wilting point. Below the effective root zone depth, half of this quantity is assumed available for evapotranspiration by capillary rise. The maximum available amount of soil moisture in a soil profile is given below:

$$M_o = (d_r + 1/2 d_c)\ (\theta_{fc} - \theta_{wp}) \qquad (1)$$

Where:

M_o = maximum available soil moisture for evapotranspiration when soil is at field capacity (m);
d_r = effective root zone depth (m)
d_c = thickness of capillary zone (m)
θ_{fc} = soil water content at field capacity ($m^3.m^{-3}$)
θ_{wp} = soil water content at wilting point ($m^3.m^{-3}$)

The soil moisture which is not available for evapotranspiration is given by:

$$M_u = d_d\ \theta_{fc} - \{(d_r + 1/2 d_c)\ (\theta_{fc} - \theta_{wp})\} \qquad (2)$$

Where:

M_u = soil moisture which is not available for evapotranspiration (m)
d_d = drain depth (m)

In the saturated reservoir, the amount of drainable water is directly related to drainable porosity and average watertable depth and given by:

$$M_{dr}(t) = \mu\ h(t) \qquad (3)$$

Where:

$M_{dr}(t)$ = amount of drainable water (m);
μ = $(\theta_s - \theta_{fc})$ = drainable porosity ($m^3.m^{-3}$);
θ_s = saturated soil moisture fraction ($m^3.m^{-3}$);
$h(t)$ = watertable elevation above drain level at any time (m).

The surface flow irrigation (border strip) is considered as a two-dimensional process. The transport of salts either as downward movement due to recharge and leaching, or as upward movement due to evapotranspiration and seepage is modelled by subdividing the soil profile into a number of layers. Through the boundary of each layer, transport of salts takes place by mass transport of water. For both rainfall and irrigation, the fluxes between the different layers are determined on the basis of the water balance of each layer.

Input and Output Parameters: The basic input parameters used in the model are grouped in four categories:

Soil:	Infiltration rate, moisture content at saturation, field capacity and wilting point and initial soil moisture content and soil salinity at different depths (unsaturated and saturated zone)
Plant:	Plant height, soil cover, root zone and critical leaf water potential
Hydrological:	Hydraulic conductivity, depth of impervious layer, aquifer resistance, piezometric pressure, initial water table depth and ground water salinity, method of irrigation and depth and quality of each irrigation during crop growth period, depth and spacing of drains (in case of a drainage system);
Climatic:	Daily maximum and minimum temperature, rainfall, relative humidity, day length, wind velocity, evaporation from U.S. Class 'A' pan.

Daily actual and maximum evapotranspiration, capillary flux, leakage/seepage from the aquifer, depth of water stored in the root zone, water table, drainage discharge and its quality, soil moisture content and soil salinity at different depths are the main output parameters of FAIDS.

The model was calibrated by using the water levels, drain discharges and soil salinity in the area drained by horizontal tile drainage system with different spacings growing vegetable crops (brinjal (egg-plant)-tomato-potato) from 1985 to 1989 at the University Farm, Hisar (Kumar and Singh, 1999). The model was validated for another four years i.e 1989 to 1993.

Model Simulation

After successful calibration and validation of the model, a number of simulations for a period of five years considering normal rainfall and also incorporating a once in ten years maximum one day rainfall (Kumar et. al., 1995; Kumar, 1994) during the fifth year of simulation were carried out to determine optimum drain spacing and depth based on relative evapotranspiration, (ET_a/ET_p) and soil salinity in the upper 30 cm and 100 cm soil depth for vegetable crops. A number of lateral spacing and depth combinations were considered. The results of simulations are given in Tables 1 and 2.

The drain configuration of 100 m x 2.5 m and 75 m x 2.0 m results in almost identical relative evapotranspiration values in the third year considering the normal rainfall situation (Table 1). However, the average soil salinity (EC_e, electrical conductivity of saturation extract) of the upper 30 cm and 100 cm soil depth in case of the former was higher (2.16 and 3.10 $dS.m^{-1}$) as compared to the latter (1.99 and 2.86 $dS.m^{-1}$). The threshold values for the vegetable crops considered ranged between 1.8 and 2.0 $dS.m^{-1}$ (Maas, 1990, Mangal et. al., 1988). Considering the relative evapotranspiration and the ease for installation, 75 m x 2.0 m drain configuration is better than 100 m x 2.5 m. If the drain depth is further reduced in case of 75 m spacing, soil salinity increases considerably resulting in significant reduction in relative evapotranspiration. At shallower depths, the water table remains very close to the ground surface thus creating unfavourable conditions for plant growth.

A maximum one-day rainfall event (1 in 10 years) in the fifth year of simulation resulted in severe waterlogging conditions (Fig.3) reducing relative evapotranspiration considerably in drain configurations of 100 m x 2.5 m and 75 m x 2.0 m. Therefore both these configurations pose a serious risk of crop damage in case of heavy rainfall events during a particular year. Therefore, it is of paramount importance to combine surface drainage with subsurface drainage system in view of the limited infiltration capacity of the soil

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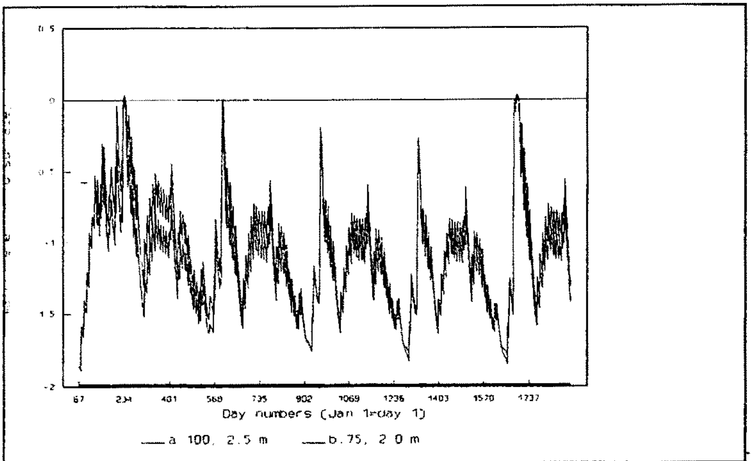

Figure 3. Simulated water levels with different drain configurations including maximum 1-day rainfall (1 in 10 years) during fifth year

Table 1: Relative Evapotranspiration (ET_a/Et_p) under different drain configurations

Sr. No.	Drain configuration (mxm)	Years				
		I	II	III	IV	V
1.	100x2.5	0.32	0.58	0.81	0.82	0.82
2.	100x2.5*	0.32	0.58	0.81	0.81	0.61
3.	75x2.5	0.50	0.77	0.78	0.79	0.79
4.	75x2.5*	0.50	0.77	0.78	0.79	0.61
5.	50x2.5	0.49	0.76	0.76	0.77	0.77
6.	25x2.5	0.49	0.75	0.75	0.75	0.75
7.	100x2.0	0.18	0.57	0.60	0.62	0.63
8.	75x2.0	0.35	0.78	0.81	0.81	0.82
9.	75x2.0*	0.35	0.78	0.81	0.81	0.61
10.	75x1.5	0.23	0.57	0.61	0.63	0.64
11.	75x1.0	0.04	0.11	0.28	0.30	0.30

In the case of the 100 m x 2.5 m drain configuration, there will be a savings of around 25 per cent of lateral pipe length, but it will be offset due to the higher initial cost of the trencher and additional dewatering costs. The cost of installation per hectare for 75 m x 2 m drain configuration is around US$ 1000 whereas for the other configuration, US$ 1025 (Anonymous, 1996). Therefore, techno-economically, the 75 m x 2 m drain configuration is the best option and is being adopted on a large scale (2000 ha) on the farmers' fields.

Table 2. Average soil salinity (EC_e) of different depths (30 and 100 cm) under different drain configurations

Sr.No.	Drain configuration (mxm)	Years				
		I	II	III	IV	V
1.	100x2.5	3.03 (7.1)	2.44 (4.0)	2.16 (3.1)	1.97 (2.6)	1.84 (2.3)
2.	100x2.5*	3.03 (7.1)	2.44 (4.0)	2.16 (3.1)	1.97 (2.6)	1.63 (2.1)
3.	75x2.5	2.41 (5.8)	1.58 (2.7)	1.29 (1.9)	1.14 (1.5)	1.06 (1.3)
4.	75x2.5*	2.41 (5.8)	1.58 (2.7)	1.29 (1.9)	1.14 (1.5)	0.93 (1.1)
5.	50x2.5	2.11 (5.3)	1.09 (1.9)	0.92 (1.2)	0.86 (1.0)	0.83 (0.9)
6.	25x2.5	2.09 (5.3)	0.99 (1.7)	0.83 (1.0)	0.79 (0.9)	0.78 (0.8)
7.	100x2.0	3.59 (8.2)	2.86 (5.0)	2.65 (3.9)	2.50 (3.4)	2.41 (3.0)
8.	75x2.0	2.80 (6.6)	2.23 (3.6)	1.99 (2.9)	1.88 (2.4)	1.70 (2.1)
9.	75x2.0*	2.80 (6.6)	2.23 (3.6)	1.99 (2.9)	1.82 (2.4)	1.49 (1.9)
10.	75x1.5	3.21 (7.8)	2.73 (4.6)	2.54 (3.7)	2.44 (3.2)	2.37 (2.9)
11.	75x1.0	4.89 (9.2)	3.79 (6.0)	3.28 (4.8)	3.08 (4.1)	2.96 (3.7)

* one-day maximum rainfall (1 in 10 years)

Values in ( ) pertain to average EC_e of 100 cm depth

RESBAL Model

The RESBAL model determines the optimum size and operation schedule of a series of reservoirs using an iterative procedure. It calculates the water level and salt concentration in a series of reservoirs based on the drainage effluent received from FAIDS. It is assumed that the first reservoir receives a certain discharge on the basis of drainage rate; its quality is calculated by FAIDS over a certain period from the given area on a daily basis. The open water evaporation from each reservoir is calculated by the Penman method in the model RESBAL. The daily rainfall are read from the same output file of FAIDS and leakage from the reservoir is estimated on the basis of specified piezometric head, leakage resistance and water level in the reservoir.

The model has a builtin provision to specify the maximum level beyond which the specific reservoir starts spilling into the next reservoir. Irrigation uptakes on a 10-day basis are specified for each reservoir. The minimum water level to be maintained in the reservoir is also defined for fish culture. The salt concentration is considered constant within it during a specified time step. When the reservoir loses water to evaporation, the quality of the evaporated water is considered fresh and the resultant salt concentration of the leftover water in the reservoir is estimated. The salt concentration of the inflowing, outflowing water, irrigation uptake and leakage is considered for the specified time step (daily basis).

The FAIDS model was used in conjunction with RESBAL to decide design specifications and an operation schedule for three connected reservoirs for irrigation, fish culture and salt harvesting for a 315 ha area at the University Farm (Singh and Kumar, 1998). The model was run for wheat-cotton rotation, with drain spacing of 72 m and depth 2 m for a period of eight years (1985-92) having four years (1985, 1988, 1990 and 1992) above normal, normal (1986 and 1991) and below normal rainfall (1987, 1989). The drainage rates and salt concentrations (output from FAIDS) were read by RESBAL. The salinity of the drainage effluent varied between 4 to 5.5 dS/m. The three reservoirs were proposed to be interconnected in series by an inverted syphon with the possibility of irrigation uptake from the first two reservoirs. In the first two reservoirs, irrigation water would not be drawn once the water level dropped to 0.7 m. This limit was introduced to grow fish in the first two reservoirs (Garg, 1994). The size of the different reservoirs was decided on the basis of salt concentration, minimum water level, irrigation uptake and no spill from the last reservoir.

The annual inflow, outflow and irrigation uptake in all three reservoirs are given in Table 3. The temporal variation in water level and water salinity in the three reservoirs are shown in Figures 4, 5 and 6. The water could be drawn from the first reservoir during all the years with different levels of uptakes. An additional irrigation could be applied in 30 to 350 ha depending upon drainage discharges. In the case of second reservoir, the irrigation uptake was possible only during three years out of eight years which was sufficient for additional irrigation in 15-160 ha. It was possible to grow fish in first reservoir during the entire period, whereas in the second reservoir, the fish culture could be followed in three years only. In the third reservoir, however, fish could be raised only during one year. The salt concentration initially in all the reservoirs was around 5 dS/m. During the summer months (April to June) when the wheat crop is harvested (first week of April) and the cotton crop just sown (3rd and 4th week of May) and the day temperature ranges between 35 and 45 degrees celsius, the drainage effluent from the drainage systems reduces considerably. The water level (depending on the year) specifically in the second and third reservoirs gets depleted due to high evaporation (8-20 mm/day) resulting in high salinity. In the present situation, a very high concentration (60-80 dS/m) was obtained during fourth and sixth year in the second and third reservoirs. The salt could be scraped, stored in bags and disposed of safely in the sea (around 600 km away from the study area) in order to maintain a favourable salt balance in the project area.

The final sizes of these reservoirs were 250 m x 200 m x 2 m;150 m x 200 m x 2 m and 250 m x 200 m x 2 m.

Table 3. Inflow (In), outflow (Out) and irrigation uptake (Irr) from all three reservoirs during the simulation period 1985 - 1992. (All values in 10^3 m^3.

	Reservoir 1			Reservoir 2			Reservoir 3		
Year	In	Out	Irr	In	Out	Irr	In	Out	Irr
1985	359	145	132	145	53	42	53	-	-
1986	233	4	210	4	-	8	-	-	-
1987	166	-	145	-	-	-	-	-	-
1988	346	139	132	139	87	-	87	-	-
1989	309	86	238	86	6	97	6	-	-
1990	8	-	58	-	-	-	-	-	-
1991	58	-	18	-	-	-	-	-	-
1992	76	-	38	-	-	-	-	-	-

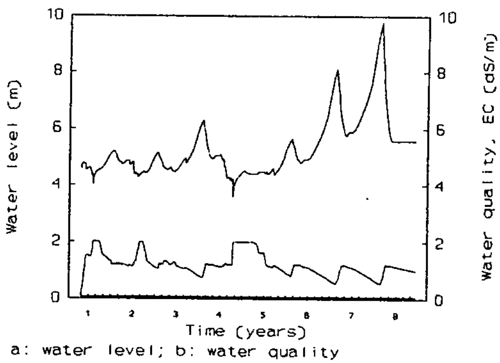

Figure 4. Temporal variation of water level and quality in the first reservoir.

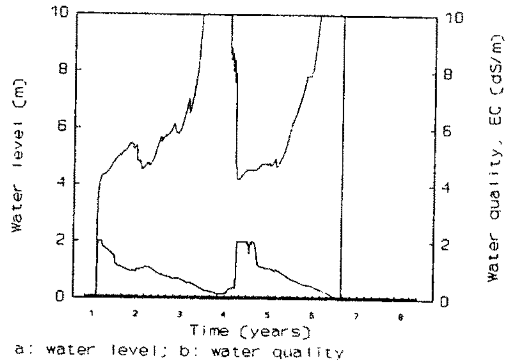

Figure 5. Temporal variation of water level and quality in the second reservoir.

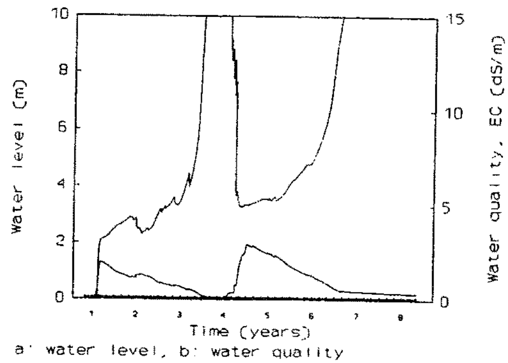

Figure 6. Temporal variation of water level and quality in the third reservoir.

SUMMARY AND CONCLUSIONS

Based on various simulation runs, the drain configuration (spacing x depth) of 75 m x 2 m depth was found to be satisfactory to maintain a favourable salt and water balance and for sustainable agricultural production. The drainage model in conjunction with the reservoir model was used to decide design specifications and an operation schedule for three connected reservoirs utilized for irrigation, fish culture and salt harvesting at the University Farm covering an area of 315 ha. The total area under the reservoirs was estimated to be about 4 percent of the total drained area. It was possible to draw water for irrigation from the first reservoir during all the simulated eight-year period and for three years from the second reservoir. The fish could be raised during all the eight years in the first reservoir and for four years and one year in the second and third reservoirs respectively.

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MARKET TRANSFORMATION OF IRRIGATION SCHEDULING IN WASHINGTON

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ABSTRACT

Washington State University is implementing a Scientific Irrigation Scheduling (SIS) Project that is being funded by the public utility districts through the Northwest Energy Efficiency Alliance (1998 through 2000). Scientific irrigation scheduling is defined as the use of crop evapotranspiration data and soil moisture sensors to accurately determine when and how much to irrigate. The project goal is market transformation. In other words, scientific irrigation scheduling will become a common practice that does not require continual government subsidy to be maintained. A 50% adoption rate will be a key indicator of market transformation in scientific irrigation scheduling.

Surveys were conducted during 1997 and 1998 to determine the status of and direction for scientific irrigation scheduling in Washington. According to the survey results, private consultants were contracted to perform irrigation scheduling on nearly 300,000 acres per year. Conservation Districts, county extension, and the National Resource Conservation Service have assisted producers in scheduling irrigation on an additional 15,000 acres per year. Individual Farm enterprises reported scheduling another 55,000 acres of irrigation on their own. The combined effort has resulted in a 17% adoption rate of scientific irrigation scheduling on an acreage basis.

Survey results also indicated that potatoes and tree fruit account for more than half of the acreage being scheduled. The main reason producers were willing to pay for irrigation scheduling is to insure the quality of high-value crops. Energy savings became important when water needed to be lifted a considerable distance; however, water conservation, high yield, fertilizer savings, and non-point pollution reduction were considered secondary benefits. Center-pivots were the most likely irrigation systems to be scheduled and a considerable proportion of

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drip and solid set sprinklers were scheduled, but a very small proportion of furrow systems and set-move sprinklers were scheduled. Of the producers who irrigated farms smaller than 1,000 acres, 75% of the survey respondents have personal computers and 50% have modems but less than 5% are using their computers to schedule irrigation.

Since computers and communication technology are available "on-farm," Washington Irrigation Scheduling Expert (WISE) has been developed as a web-linked and user-friendly software tool that brings together all the pieces needed to implement irrigation scheduling. WISE, soil moisture sensors and other tools will be promoted via traditional demonstration and educational methods but with a different emphasis. Instead of offering irrigators a free service, cooperators will be encouraged to produce their own irrigation schedules from the onset of their involvement with the SIS project and agricultural supply companies will be encouraged to add irrigation scheduling to their services. The goal of this paper and presentation is to document the status, tools, and progress of market transformation in Washington's SIS Project.

INTRODUCTION

The definition of Scientific Irrigation Scheduling (SIS) is deciding when and how much to irrigate based on physical measurements that estimate crop-water use and the soil-water status. The goal of the Scientific Irrigation Scheduling Venture in Washington is market transformation. Market transformation is an adoption process by which a product or procedure becomes a common and accepted practice that is supported by private enterprise without continual government subsidy. A 50% SIS adoption rate will be a key indicator of market transformation in Washington.

The process of transferring SIS technology to growers began over thirty years ago according to Shearer and Vomocil (1981) and Fereres (1996). These efforts have been effective in conserving water/energy (Shearer and Vomocil,1981; Dockter,1996 and Alam et al., 1996), improving crop yield/quality (Lyford and Schild, 1981; Silva and Marouelli, 1996; and Tacker et al., 1996) and reducing non-point pollution (Boesch et al., 1981; Klocke et al., 1996; and Nguyen et al., 1996). In addition, many Agricultural Consultants in the western United States have established successful irrigation scheduling businesses similar to the one described by Salazar et al. (1996).

However, there are also documented difficulties in transferring SIS technology to growers. Clyma (1996) believes there has been a decrease in the practice of SIS. Shearer and Vomocil (1981) reported that most of the successful SIS programs in Oregon disbanded once the programs were no longer offered as free services. Koegelenberg and Lategan (1996) from South Africa believe that only consultants can apply the technical expertise necessary to implement irrigation scheduling correctly. Buchleiter et al. (1996) reported a combined savings of $23.7/ha in water, energy and labor on a 1700 ha farm in Kansas at a cost of $8.00 /ha. However, an attempt to sell similar SIS services to neighboring Kansas farms was unsuccessful at this level of return.

As for the future of SIS technology transfer, Howell (1996) states that there has been little change in SIS theory and methodology over the last twenty-five years; however, there have been significant changes in information technology that need to be applied to update SIS practices. Lamacq et al (1996) found that growers schedule irrigation on a whole farm basis and not strictly by the requirements of individual fields. This research suggests that the SIS techniques that we promote must be applicable to the entire farming system. Shearer and Vomocil (1981) remind us that adoption of fertilizer and weed control practices required sustained and concentrated support by both industry and educational institutions to accomplish market transformation.

STATUS OF IRRIGATION SCHEDULING IN WASHINGTON

1998 SURVEY OF IRRIGATION SCHEDULING SERVICE PROVIDERS

- 9 Consultants
- 1015 Clients
- 290,756 acres contracted for Irrigation Scheduling out of 2,120,000 irrigated acres in Washington (13.7%)

Ag. consultants who provide irrigation scheduling services participated in a telephone survey prior to the 1998 growing season. In Washington, nine consultants responded to the survey that required forty-five minutes of phone time; however, most spent about two hours talking about their business. The combined effort from these nine firms resulted in over 1,000 clients and nearly 300,000 acres contracted for irrigation scheduling. This acreage represents 13.7% of Washington's 2,120,000 irrigated acres.

CONTRACT ACRES BY CROP

- 120,000 ac - Potatoes
- 32,600 ac - Tree Fruit
- 25,000 to 15,000 ac - Alfalfa (seed also),Sweet Corn, Grain Corn, and Onions
- 15,000 to 4000 ac - Sugar Beets, Grass Seed,Beans, Small Grain, Peas, Wine Grapes, and Poplars
- < 500 ac - Hops, Concord Grapes, Carrots

Potatoes were the crop most likely to be scheduled by a professional service and tree fruit was the next highest. Together they account for more than half the acreage scheduled professionally. Alfalfa, sweet corn, grain corn, and onions were scheduled at between 25,000 to

15,000 acres each. From 15,000 to 4,000 acres each of sugar beets, grass seed, beans, small grain, peas, wine grapes, and poplars were being scheduled. Very little professional irrigation scheduling is being performed on hops, concord grapes, and carrots.

Center-pivot irrigation systems were the most likely to be contracted for irrigation scheduling at 217,000 acres. Solid set and drip (includes micro spray) were the next largest group at 30,000 acres each, while very little irrigation was being scheduled professionally under furrow and set move systems. These survey results were also compared to the irrigation system acreage in Washington State as reported in the Irrigation Journal. Nearly, fifty percent of center-pivot acreage was being scheduled by professional services. This seemed unduly high and perhaps the total center pivot acreage is under reported. However, center-pivots are predominantly used to grow potatoes, the most scheduled crop, and water application can be easily controlled under center-pivot irrigation. Both solid-set sprinkler and drip irrigation had a higher percentage of professional irrigation scheduling than furrow and set-move sprinklers, possibly because they are extensively used on high-value crops such as vines and tree fruit and they are also easy to automate.

CONTRACT ACRES BY IRRIGATION SYSTEM

	Furrow	Set Move	Solid Set	Pivot	Drip
Survey	9850	3900	30,601	216,905	29,300
State	510,00	800,000	200,000	475,000	100,000
	1.9%	0.5%	12.2%	45.7%	29.3%

Most irrigation-scheduling consultants use the hand/feel method to compare with their soil moisture monitoring devices. The most prevalent monitoring device was the neutron probe, used by five of the nine consultants. Three of the consultants used gravimetric sampling in shallow rooted crops where a neutron probe might not be as effective. In addition, several consultants were promoting one of the less conventional methods of soil-moisture monitoring: Aqua-Flex, Aqua-Tel, Time Domain Reflectometry (TDR), and Frequency Domain Reflectometry (FDR).

SOIL MOISTURE MONITORING

Hand/Feel	9 out of 9
Neutron Probe	5 out of 9
Gravimetric	3 out of 9
Aqua-Flex	1 out of 9
Aqua-Tel	1 out of 9
TDR	1 out of 9
FDR Troxler Sentry	1 out of 9

EVAPOTRANSPIRATION

• On-site Weather Station	2 out of 9
• PAWS Weather Station	8 out of 9
• AGRIMET Weather Station	6 out of 9
• Historical	2 out of 9
• Change in Soil Moisture	2 out of 9

Most irrigation scheduling providers rely on a combination of PAWS and AGRIMET weather stations to estimate crop ET. Two of the consultants set up on-site weather stations for clients to calculate ET right on their property. Two consultants indicated that they used the change in water content measured at their soil moisture monitoring sites to adjust predicted ET rates. Seven out of nine consultants use a combination of present soil moisture status and predicted ET to calculate operation times for clients' irrigation systems.

Irrigation scheduling is beneficial in many ways, but consultants were asked which benefits motivated clients to pay for their services. When clients were pumping from deep wells or lifting water long distances from rivers, water and energy conservation were important because operating expenses could be lowered significantly. Another key reason to pay for irrigation scheduling was improved crop quality. For many high-value crops, quality is the key to better price and proper irrigation is an important factor in maintaining high quality. Pressure to reduce agricultural pollutants was not described as an important reason to pay for irrigation scheduling even though environmental issues are becoming more prevalent.

KEY REASONS CLIENTS PAY FOR IRRIGATION SCHEDULING

• Short of Water	1 out of 9
• Save Water	3 out of 9
• Save Energy	4 out of 9
• Reduce Pollutants	1 out of 9
• High Yields	3 out of 9
• Crop Quality	7 out of 9
• Save Fertilizer	2 out of 9
• Size of Farm	1 out of 9
• Crop Value	2 out of 9
• Reduce Agronomic Problems	0 out of 9

Seven of the irrigation scheduling providers said their business was expanding slightly to moderately and those who said their business was not growing wanted to keep the business at its present size but felt they could expand if they desired. In addition to this favorable business climate among existing consultants, new irrigation scheduling ventures are getting started that utilize some of the newer soil-moisture measuring

THE BUSINESS CLIMATE

- Growth of business - 7 out of 9 expanding
- Identified 3 new firms offering irrigation scheduling
- A 1 to 1 benefit ratio to non contracted acreage

technology. Overall, consultants felt an additional acre benefited from every acre under contract.

1997 IRRIGATION SCHEDULING SURVEY OF WASHINGTON STATE PRODUCERS

- 199 Surveys Returned
- 105,000 Acres out of 2,120,000 Irrigated Acres in Washington

The SIS provider survey gives a picture of irrigation scheduling in Washington State from the consultants' perspective. Individual Grower's are also scheduling irrigation for themselves.

In the July 1997 issue of the *Washington Irrigator Newsletter*, a survey of scientific irrigation scheduling practices was included. Of those receiving the newsletter, 199 surveys were returned by Washington irrigators. representing 105,000 acres of Washington's 2,120,000 irrigated acres.

SELF-IMPLEMENTED SCIENTIFIC IRRIGATION SCHEDULING

	by acreage
• Use ET and Soil Sensors	77%
• Professional Scheduling Service	14%

Scientific irrigation scheduling (SIS) is defined as the use of both soil moisture sensors and crop evapotranspiration (ET) data to determine when and how much to irrigate. According to this definition, SIS is being practiced on 77% of the reported acreage. This high percentage is probably not representative of the entire state because those who practice SIS are more likely to return a survey than those who are not as interested in SIS. However, professional consultants were only responsible for implementing SIS on 14% of the survey acreage. Therefore, the survey represents the perspectives and practices of irrigators who implement SIS on their own.

IRRIGATION SYSTEMS USED IN IRRIGATION SCHEDULING

	Furrow	Set Move	Solid Set	Pivot	Drip
• Irrigation Systems being Scheduled in Survey	7%	10%	9%	71%	3%
• Irrigation Systems in Washington	24%	38%	10%	24%	4%

Most SIS is being implemented with center pivot irrigation (77%). Furrow, set-move sprinklers, solid-set sprinklers, and drip are each less than 10% of the SIS acreage. However, solid-set sprinklers and drip systems only account for 10% and 4% of the irrigated acres in Washington, respectively. Therefore, irrigation of solid-set and drip systems is being scheduled at a higher rate than furrow and set-move sprinklers systems that account for 24% and 38% of Washington's irrigated acres, respectively.

The farm size of survey respondents varied from 2 to 24,000 acres. It was assumed that a producer with 24,000 acres would have a different perspective on irrigation scheduling than one with 2 acres. Therefore, the survey data was split into two groups: producers with more than 1,000 acres (large) and those with less than 1,000 acres (small).

FARM SIZE MAKES A DIFFERENCE

	# Surveyed	Total Acreage	Average Acreage
SMALL under 1000 ac.	182	26,852	147
LARGE over 1000 ac	17	77,973	4589

Both large and small operators reported high utilization of the feel/appearance method (above 79% by acreage) to determine the status of soil moisture. As for sensors, both groups were most likely to use a neutron probe and least likely to use Time Domain Reflectometry (TDR). However, the rate of sensor utilization was much greater in the large farm group. As an example, the neutron probe was being used on 80% of the acreage in the large farm group and on only 20% of the acreage on smaller farms. Private companies are presently marketing many new soil moisture sensors and the types of sensors used in Washington may change drastically.

SOIL MOISTURE MONITORING

by acreage	*small*	*large*
Hand/Feel	79.1%	94.4%
Neutron Probe	19.8%	80.5%
Tensiometers	13.5%	41.0%
Gravimetric	9.0%	33.0%
Moisture Blocks	3.1%	1.5%
TDR	0.0%	1.5%

Crop evapotranspiration (ET) is another important tool in Scientific Irrigation Scheduling. Again, large farms reported greater use of ET information than the smaller farms, 90% versus 35% by acreage, and the sources of ET were also quite different. The small farm group predominantly used nearby weather stations, daily newspapers, and on-site evaporation pans, while the large farms used ET from computer software, nearby weather stations, and on-site weather stations.

EVAPOTRANSPIRATION

	35% small	*89% large*
•	by acreage	
• On-site Weather Station	2.2%	29.2%
• Nearby Weather Station	20.2%	60.5%
• Historical on Computer	2.6%	72.6%
• On-site Evap. Pan	6.8%	0.0%
• Daily Newspaper	12.1%	4.0%

COMPUTERS ON-FARM

	small	*large*
•	by survey	
• Used to Schedule Irrig.	3%	47.1%
• Own a Computer	77%	94.1%
• Connected to Modem	50.8%	52.9%

Finally, computers help producers implement irrigation by providing access to crop ET, processing soil moisture readings, and forecasting operation times for irrigation systems. The survey revealed that 77% of the small operators owned computers but only 3% used them to schedule irrigation. On the large farms, 94% owned computers and 47% were used for SIS. In both groups over 50% had modem connections.

The newsletter survey shows how producers are implementing SIS for themselves. Yet it does not reveal how producers have learned to incorporate SIS into their operations. The final survey explains one of the mechanisms by which irrigation scheduling technology has been transferred to producers.

1998 IRRIGATION SCHEDULING SURVEY OF GOVERNMENT AGENCIES

- 10 of 41 Conservation Districts, NRCS, and Extension Offices provide Irrigation Service or Assistance.
- 234 Irrigators are Participating in Scheduling Programs
- 14,064 acres Benefiting from Irrigation Scheduling

A telephone survey of government agencies involved in irrigation scheduling was conducted in the fall of 1998. A total of 43 National Resource Conservation Service, County Extension, and Conservation District offices were surveyed and 11 of these were conducting field programs in irrigation scheduling. In these programs, 234 clients were involved effecting 14,064 irrigated acres.

The main irrigation scheduling tools used by government agencies are soil moisture monitoring and crop ET. The soil moisture sensors listed from most to least used are: tensiometers, granular matrix sensors, capacitance probes and the neutron probe. The sources of crop ET listed from most to least used are: PAWS, historical, and AgriMET.

TOOLS USED BY AGENCIES TO SCHEDULE IRRIGATION

- Soil Moisture Sensors - 7 using Tensiometers, 4 using WaterMarks, 2 using Troxler Sentry, and 1 using Neutron Probe.
- Crop Water Use Data - 7 using PAWS, 2 using Agrimet, and 5 using Historical ET.

Government agencies also provided educational opportunities for growers to learn about irrigation scheduling. During 1998, 11 irrigation scheduling workshops were conducted with a combined attendance of 254 irrigators. The 11 agencies already conducting irrigation scheduling programs said they were interested in a joint effort with the SIS Venture being implemented by WSU's Extension Irrigation Speacialist. An additional 12 agencies said they would like to start a joint irrigation scheduling program.

EDUCATIONAL PROGRAMS OFFERED BY AGENCIES

- 11 Irrigation Management Workshops were Attended by 254 Producers.
- 23 Agencies Expressed Interest in Joint Field Programs and/or Workshops

Five important conclusions from this survey are: 1) 9 consultants are scheduling the largest proportion of irrigated acreage (mostly high value crops), 2) a significant number of Washington producers are implementing SIS on their own, 3) large farming operations are making SIS a standard practice, 4) a majority of producers have the infrastructure for computer based irrigation scheduling but most are not using their computers for this purpose, and 5) 10 government agencies are helping producers implement irrigation scheduling and more agencies would like to start SIS programs). The combined effort has resulted in approximately 370,000 acres involved in SIS out of Washington's 2,120,000 irrigated acres. This amounts to an adoption rate of 17% by acreage and is a third of the way to the goal of 50% adoption for market transformation of SIS.

STRATEGY FOR SIS IMPLEMENTATION

Traditionally, most irrigation scheduling programs offer free or cost-shared services to help educate producers regarding new techniques. However, it was determined that such a program would not have been effective for several reasons. First, providing free services would have competed with existing services and programs creating either redundant services or alienation of irrigation scheduling services providers. Another key factor in the decision was finite funds. The SIS grant from the Northwest Energy Efficiency Alliance provides funds for 1.3 full time equivalent employees which is not sufficient to provide SIS service to the entire state of Washington. But the argument against traditional methods was not simply bound by issues external to producers. It was also thought that if producers took an active role in SIS practices, the experience would allow them to make better decisions regarding if SIS was effective for them, if they were capable of doing it themselves, or if they saw hiring a consultant as being cost-effective. Getting the latest SIS tools in the hands of the producer would also help researchers and extension workers determine which methods were the most cost-effective and beneficial given the individual variables of different farms and farmers.

Therefore, a program was developed that would facilitate existing programs through traditional extension education, development of web pages and online computer programs to create SIS market transformation in the state rather than compete. This is being accomplished in three broad categories. The first is to cooperate with existing SIS promoters: regional extension agents, conservation districts, natural resource conservation services, public utility districts, ag chemical suppliers, irrigation equipment suppliers, and private consultants. Second, create marketing and technical tools to help existing SIS providers and encourage new companies to provide SIS services. Finally, establish educational and technical tools (including information technology) that allow producers to implement SIS on their own.

Technical and Marketing Tools for the Information Age:

The Washington Irrigation Scheduling Expert (WISE) Software is being developed to meet the needs of Washington Irrigators. WISE is written in JAVA with NetBeans DeveloperX2 components to allow cross platform operation and easy access to reference evapotranspiration (ET) from Washington's 59 Public Agriculture Weather Stations (PAWS). The graphical user interface is intuitive and will help the user input their field specific parameters such as crop type/timing, soil moisture and irrigation system specifications. WISE employs a short-term water balance that can be adjusted for soil moisture conditions. WISE is not a black box calculation of when and how much to irrigate since important steps are displayed and made apparent to the user. This feature also makes WISE an educational tool that teaches the principles of irrigation scheduling.

An alpha version of WISE was tested with irrigators during the 1999 growing season. A beta version was completed by the end of 1999 and this release is stable enough for use in 2000 growing season. Producers and SIS service providers can download WISE from http:\\wise.prosser.wsu.edu. To make the most of WISE a PAWS internet account is highly recommended.

A SIS web site is also being developed. This site will provide access to PAWS, WISE, SIS service providers, newsletters, publications, presentations, event calendar, and a SIS list serve. The site is located at http:\\sis.prosser.wsu.edu.

Traditional Education and Marketing Tools

Field demonstrations have become more focused since all on-farm experiments are driven by testing and perfecting SIS. Soil-moisture sensors marketed in Washington are being compared under different soils, irrigation systems and crops. These have been placed in locations across the state where cooperating organizations will use them in field days to promote SIS. The results from the sensor comparisons are also being used in SIS workshops.

SUMMARY OF SIS OUTREACH EFFORTS

- 29 Workshop Presentations with 1,278 Contacts
- 12 Field Day Presentations with 401 Contacts
- 24 Articles in Newsletters and Popular Press
- 8 Soil Moisture Sensor Comparison Sites
- 8 Cooperators demonstrating SIS
- 207 Contacts for Technical Assistance (one-to-one)

SIS cooperating farms are monitoring soil moisture with a sensor of their choice and generating schedules from WISE. The SIS project will provide free access to PAWS, teach cooperators how to use WISE and confirm their method of soil-moisture monitoring with neutron probe readings. The SIS project will also monitor their irrigation amounts and timing with a micro-logger. Each of these steps is intended to move cooperators toward self implemented irrigation scheduling or the realization that they should pay a service provider. Workshops on WISE and scheduling methods are also training and encouraging producers to implement SIS.

Finally, the written media is also utilized. Newsletters, articles, and a brochure have been published to educate and promote SIS. Other media formats such as television and radio may be utilized as the SIS project progresses.

Collaboration Strategy

Since the focus of the Washington SIS program and the way it is marketed has fundamentally changed, many cooperators will have the opportunity to learn self-implemented SIS in lieu of WSU providing free services to a few clients. Instead of marketing for an isolated WSU Program, the SIS project will seek to promote and prepare other provider organizations to participate in the market transformation process.

Since WSU will avoid duplicating existing programs, funds and engergies can be funneled into developing new tools to be shared with anyone interested in using or promoting SIS. Some of the ways the Washington SIS program can support partner organizations include the following:

- Listing on SIS Web Site along with SIS Information.
- One Advertisement/Article per year in "Washington Irrigator Newsletter."
- Use of Washington Irrigation Scheduling Expert Software and PAWS Data.
- Automated Monitoring of Irrigation System On Times at an affordable price.
- Client Training in SIS via Workshops and Field Days.
- WSU Technical Support of PAWS and WISE.
- Limited Field Support (WISE set-up and check-ups).
- Testing of Soil Moisture Sensors.

In addition, a brochure has been published which although developed and printed by WSU, is free to cooperating providers to use with prospective clients (either public or private). A space has been left blank to allow individual providers to personalize the brochure with a stamp or business card.

In return for such support, partner organizations will be required to:

- Provide Soil Moisture Sensors for Testing at WSU.
- Purchase a PAWS Subscription after their program is established.
- Receive Training in PAWS and WISE.
- Work with Clients to Monitor Soil Moisture and Produce Irrigation Forecasts.
- Organize and Set-up Irrigation Workshops and Field Days.
- Report Clients Assisted under SIS.

Each of these commitments is design to ensure reliable and scientific irrigation scheduling is dispersed to all participants.

RESULTS AND CONCLUSIONS

As of January 2000, Washington's agricultural service industries are showing signs of market transformation in SIS. Two of the nine existing SIS service providers plan to use WISE with some of their clients while another existing service providers will sell soil moisture sensing devices with SIS training for producers who desire to implement their own irrigation

MARKET TRANSFORMATION INDICATORS

- 1 of 9 existing SIS provider starting to sell sensors
- 2 of 9 existing SIS providers using WISE
- 6 of 8 new SIS companies selling sensors
- 4 of 8 new SIS companies providing field service
- 3 of 4 new SIS providers plan to use WISE
- 20 individual WISE software downloads

scheduling programs. Since the initial survey of SIS providers in the spring of 1998, eight more Washington based companies will start marketing SIS. Six of the eight are selling new soil moisture monitoring devices and four companies will provide on-farm scheduling services. Of the four companies planning to provide direct SIS service three intend to use WISE. WISE has also been downloaded by nearly twenty individuals.

Future SIS surveys should reveal the extent of SIS penetration into new markets. In many ways, the SIS market is being driven by new information technology that allows businesses to better serve their customers and by the need to reduce environmental degradation caused by irrigated agriculture. Therefore, the future looks bright for market transformation of SIS. Funding for the Washington SIS Venture was provided by the Northwest Energy Efficiency Alliance (NEEA).

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PARTICIPATORY IRRIGATION RESEARCH AND DEMONSTRATION IN CANADA

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ABSTRACT

The importance of producer and public participation in research, demonstration and extension is becoming better recognized on a world-wide basis.

Currently in Agriculture & Agri-Food Canada, much emphasis is being placed on identification, recognition and satisfaction of client needs. Partnerships and co-operative ventures with the private sector and other government agencies are being encouraged and pursued. The Prairie Farm Rehabilitation Administration (PFRA), as part of Agriculture & Agri-Food Canada, has been a leader in encouraging these partnerships, particularly as they relate to irrigation research and demonstration and their effect on rural development and environmental sustainability. Today, in co-operation with private industry and the provincial government, PFRA successfully operates research and demonstration centres at Outlook, Saskatchewan (Canada-Saskatchewan Irrigation Diversification Centre) and Carberry, Manitoba (Manitoba Crop Diversification Centre).

The partnership at the Canada-Saskatchewan Irrigation Diversification Centre was finalized in July, 1998. In view of the newly formed partnership, a results-based strategic planning session was held to determine the future direction of the Centre. Participants in the workshop included a broad range of producers, industry, university and government stakeholders. The workshop was designed to achieve a consensus on a vision for the role of the Centre, the obstacles which may prevent achieving the vision and the strategic direction the Centre must take. This participatory workshop was successful in providing this information.

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INTRODUCTION

The importance of producer and public participation in research, demonstration and extension is becoming increasingly well recognized on a world wide basis. Irrigation systems are complex "socio-technical" systems which involve interaction between the physical environment, the application of technology, the practice of agriculture and the often competing interests of multiple stakeholders. Consequently, sound technical analysis, astute management and the active participation of stakeholders is critical to realizing a positive return to societies investments in irrigated agriculture (Vermillion & Brewer, 1996).

The challenge for researchers today is to develop economically viable technology that is easily adaptable to the rural society (Tollefson & Wahab, 1996). Much of the developed world has traditionally followed the paradigm, whereby research is conducted at universities and the resultant technology is transferred through various extension mechanisms to the producer (Tollefson, 1992). Hill & Tollefson (1996) suggest that increased farmer participation is critical because it provides greater accountability resulting in increased productivity.

The Prairie Farm Rehabilitation Administration (PFRA), as part of Agriculture & Agri-Food Canada, has been a leader in encouraging partnerships and private sector involvement in irrigated research, demonstration and extension. The emphasis is on rural development and environmental sustainability. Today, in co-operation with private industry, and provincial governments, PFRA successfully operates irrigated research and demonstration centres at Outlook, Saskatchewan, and at Carberry, Manitoba.

The following paper outlines the role, operation, achievement and future direction of these facilities.

CANADA-SASKATCHEWAN IRRIGATION DIVERSIFICATION CENTRE

Background

The Canada-Saskatchewan Irrigation Diversification Centre (CSIDC) originated as the Prairie Farm Rehabilitation Administration (PFRA) Farm at Outlook, Saskatchewan. The PFRA Pre-development Farm was established in 1949, prior to the construction of the Gardiner Dam. The farm was designed to demonstrate irrigation technology to assist farmers in their transition to irrigated agriculture. Upon completion of the Gardiner Dam and the formation of Lake Diefenbaker, the farm became known as the Demonstration Farm and served a useful role in demonstrating irrigation technology.

It was recognized, however, that additional research and demonstration support was necessary if the project was to be successful. Individual programs by Agriculture & Agri-Food Canada, PFRA, the University of Saskatchewan and Saskatchewan Agriculture & Food, although limited, were underway. They addressed specific organizational or scientific objectives often on an independent basis. A need existed for a co-ordinated, co-operative program.

The Saskatchewan Irrigation Development Centre (SIDC) was established in 1986, as a jointly funded federal/provincial agency as a result of a Memorandum of Understanding (MOU) between Agriculture & Agri-Food Canada, PFRA and Saskatchewan Agriculture. The MOU made SIDC responsible for planning and co-ordinating all federal and provincial irrigation research and demonstration activities in the province of Saskatchewan.

To facilitate this role required a major upgrading of physical facilities. This included replacement of the water supply canals by a buried pressurized water supply line, the purchase of three electrical centre pivots and a specially designed research linear system. In addition, surface drainage was improved and subsurface drainage installed where necessary. A full line of small plot research equipment was purchased along with the construction of a modern office/laboratory complex. Scientific and support staff were hired to conduct programs responsive to client needs. These changes helped make SIDC a world quality irrigation R & D facility.

In recognition of the importance of partnerships and, particularly, the role of industry in the partnership, a new MOU was signed in 1998. This MOU now included Canada (Agriculture & Agri-Food Canada, PFRA), Saskatchewan (Sask Water) and Industry{(Saskatchewan Irrigation Projects Association (SIPA) and the Irrigation Crop Diversification Corporation (ICDC)} at the management table of the newly named "Canada-Saskatchewan Irrigation Diversification Centre" (CSIDC). This agreement places CSIDC in a strong position to meet the future needs of its clients.

<u>CSIDC Mandate</u>

The mandate of CSIDC is to help maintain a viable agriculture industry, to support a sound rural economy, and to preserve a healthy environment. To achieve this mandate, CSIDC strives to:

1. Identify higher value cropping opportunities through market research to

help target the research and demonstration effort.

2. Conduct, fund and facilitate irrigated research and demonstration to meet the needs of irrigation producers and the industry.

3. Develop, refine, and test methods of diversifying and intensifying irrigated crop production in co-operation with outside research agencies.

4. Develop and demonstrate sustainable irrigated crop production methodology.

5. Promote and extend sustainable irrigated crop production methodology.

6. Evaluate the environmental sustainability of irrigation through investigation of its impact on natural resources.

7. Promote a Western Canadian approach to irrigation research and demonstration by co-operating with staff from similar institutions and from industry. Increased levels of co-operation in marketing, research and demonstration support diversification and value added processing. Transfer of such technology strengthens the industry.

The CSIDC operates programs in specialty and field crop agronomy, environmental sustainability, market analysis, technology transfer and on-farm field demonstrations to help meet the needs of its clients.

Organization

The Executive Management Committee (EMC) is the main governing body of the Centre. The EMC has equal representation from Canada, Saskatchewan and Industry. Each of Canada, Saskatchewan and Industry (ICDC) designates one of its appointees as joint chair. The chair of the EMC rotates annually among the three joint chairs. The EMC shall meet at least twice per year.

Decisions of this group are reached by consensus. The EMC is responsible for the overall workplan and broad policy direction of CSIDC.

Each of the partners agree to work co-operatively and provide financial and in-kind support to the Centre. Canada agrees to provide management, staff and facilities support.

Achievements

Research and demonstration activity conducted, funded and facilitated by CSIDC have resulted in many achievements. The following are some of the more noteworthy:

Crop Diversification:

1. In 1986, there was virtually no dry bean production in the irrigated areas of Saskatchewan. More than a decade later, in 1999, there were 8,000 acres of dry bean. Research and demonstration conducted by CSIDC has played a significant role in this expansion.

2. Canola is a major crop in the irrigated areas of Saskatchewan (20,000 acres). This expansion is due in part to the identification by CSIDC of a high yielding, lodging tolerant variety (Global) well adapted to irrigated conditions. Newer varieties have since been identified by CSIDC which have a 10 - 15% yield advantage over Global.

3. CSIDC played a pivotal role in the identification of Northern Vigor[5] of seed potatoes. Saskatchewan grown seed produces on average a 20% yield increase compared to locally grown seed when planted in the United States or Mexico. A major acreage of seed potatoes is now being produced under irrigated conditions in Saskatchewan. This acreage doubled between 1993 and 1996 and is expected to expand in the future.

4. CSIDC assisted industry in evaluating spearmint and peppermint production under irrigated conditions. Positive results have lead to the construction of a distillation plant in the Outlook area to process the oil.

Intensification:

1. A full complement of crop variety testing is now being conducted for many crops grown under irrigated conditions. An updated irrigated crop variety guide is published annually and is distributed to irrigators.

2. Soil test benchmarks and fertilizer recommendations have been re-evaluated for irrigated conditions.

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[5]Northern Vigor™ is a registered trademark of the Saskatchewan Seed Potato Growers Association.

3. Production knowledge such as seeding dates and rates, row spacing, and depth of planting, have been evaluated and refined for many of the commonly grown irrigated field crops and for a wide variety of specialty and horticultural crops.

4. Trials at SIDC have shown that it is possible to reduce energy costs of center pivot irrigation by up to 50% and to improve application efficiency using lower elevation spray application (LESA).

Environment:

1. An evaluation of the effect on groundwater quality of agrochemicals applied to irrigated cropland is being conducted. A large scale subsurface drainage system has been installed which allows replicated field scale investigations to be conducted on the effect of irrigated crop management practices on groundwater quality.

2. The effect of irrigation on soil chemical and physical properties and long-term productivity have been studied.

3. A unique field scale plot has been used to demonstrate the reclamation of a salt affected area using subsurface drainage and leaching.

4. SIDC expertise has been recognized and utilized in the international sphere. This includes technical and administrative support of the CIDA sponsored Canada/Eqypt National Water Quality and Availability Management program (NAWQAM) and the water savings component of the Hebei dryland project in China. SIDC staff are also involved in international technical committees.

Public Awareness

In 1998, more than 2,000 visitors viewed the Centre. Twenty-four guided tours were conducted, several of which were for foreign delegations. Highlights include the annual field day, the evening tour along with a number of commodity based tours. In 1998, more than 500 people witnessed the signing of the CSIDC Memorandum of Understanding by federal and provincial ministers, and industry representatives.

Public presentations are routinely made at scientific and extension events.

Future

CSIDC recently completed a strategic planning process which involved stakeholders, ie: producer, industry, university and government. The following recommendations were developed at that workshop and will be utilized to help shape the future direction of CSIDC. They included:

1. Develop a CSIDC Business Plan.
2. Secure appropriate irrigation R & D funding through A-level funding (federal and provincial), federal/provincial/ industry agreements, and research/ industry contracts.
3. Commission the documentation of irrigation personnel, and R and D information applicable to Saskatchewan conditions in an electronic database.
4. Encourage collaborative R & D partnerships on a prairie-wide and on an international basis.
5. Commission the creation and distribution of an updatable irrigation manual for the Canadian Prairies.
6. Define requirements for and identify mentor irrigators to be involved in a farmer-to-farmer information exchange.
7. Establish four irrigation demonstrations spoke sites located province-wide.

These recommendations are currently being implemented by the CSIDC Executive Management Committee.

MANITOBA CROP DIVERSIFICATION CENTRE (MCDC)

Background

The Manitoba Crop Diversification Centre was established in 1993 under a ten-year agreement among the Government of Canada (PFRA), the Government of Manitoba and Industry (Manitoba Horticultural Productivity Enhancement Centre Inc. (MHPEC). In many respects, it was modelled after the CSIDC. The goal of MCDC is to develop and operate a Centre through which crop diversification and production enhancing technologies can be investigated and demonstrated for the benefit of the agriculture industry in Manitoba.

All three partners in MCDC are actively involved through participation in the Centre Management Program Advisory Committees. Input from other industry and stakeholder representatives is also obtained at annual program advisory meetings.

Infrastructure

The MCDC headquarters site is located at Carberry, Manitoba. It operates satellite sites at Portage la Prairie and Winkler, Manitoba.

The Carberry site is located on one-half section of excellent agricultural land. Buildings include an office-lab-classroom complex, a sample processing area, shop, machinery, chemical and grain storage. Equipment for most operations is owned, while some field and research operations are contracted or conducted by project co-operators. A modern irrigation system has been installed, which permits irrigation of approximately 70 ha of the land, using three centre pivots and two linear-move systems. These are well-adapted to meet the requirements of irrigation research trials. This capability is unique to MCDC in Manitoba. Most irrigation research in Manitoba requiring good control is now conducted at MCDC.

The Portage la Prairie site was previously an Agriculture and Agri-Food Canada Research Centre sub-station. Two linear-move field irrigation systems and an irrigation water supply delivery system were installed to facilitate irrigation at this site.

The Winkler site consists of approximately 16 ha of sandy loam, mostly irrigated by a linear-move field system. There are no buildings or full-time staff on-site. Most field and plot operations are carried out by staff operating from the Portage la Prairie site.

The three MCDC sites are strategically located in areas of Manitoba with high-value irrigated crop production potential and a range of representative soils. MCDC is also affiliated with the Parkland Crop Diversification Foundation (headquartered at Roblin) and with the Souris Valley Irrigation Centre at Melita.

MCDC Mandate

The primary goal of MCDC is the investigation and demonstration of sustainable crop production through crop diversification and intensification production practices.

The Centre accomplishes this by:

1. Identification of the needs of horticultural and other producers, and of industry,
2. Support of the development of value-added processing in Manitoba,

3. Investigation and demonstration of crop diversification and environmentally sound management practices under irrigation at strategic locations in the province,
4. Contributing to public awareness of the role of agriculture,
5. Facilitation of applied research and demonstration activity,
6. Development of production technologies.

Much of the Centre's current activity is conducted in co-operation with outside agencies, groups and individuals. The Centre provides technical and facilities support, along with an irrigated land base to assist irrigated research and demonstration activities. Potato and special crop production agronomy, and groundwater quality constitute the research program. The field demonstration program focuses on field, forage, herb and spice, fruit and nutraceutical crops.

Extension

Results of the MCDC program, and information on agriculture diversification, potato production, irrigation, and environmentally responsible agriculture, are extended to the industry and the public by several means. The Centre's Annual Report and Newsletter (*The Rainbow*) are widely distributed. Staff participate in trade shows and seminars, organize extension meetings, host annual tours at each site, and respond to office and telephone inquiries. Since most projects are co-operative, the co-operating agencies also transfer information through established contacts and mechanisms.

Results, The Future

The value of diversification to the agricultural and rural economy is well accepted. Higher value crops, although often more difficult to produce and market, have potential farmgate returns far in excess of more traditional crops. This is a major emphasis for MCDC. The Centre also plays a key role in monitoring and promoting the environmental sustainability of intensive field agriculture.

MCDC is in its sixth field season, and has recently had an independent program evaluation to assess its progress in meeting the program objectives. Recommendations were made for consideration by Centre Management, to allow it to better define and focus the Centre's role and activities now that it is well-established as an agency. The general support indicated by partners and stakeholders for the future operation of MCDC indicate the success to date and future potential of the Centre in playing a meaningful role in the development of agriculture in Manitoba.

ALBERTA

The province of Alberta has the largest irrigated acreage in Canada. Currently, discussion and studies (Agri-Team Consultants) are underway regarding environmentally sustainable irrigation crop diversification initiatives in Alberta. The approach would again be a partnership with two levels of government and industry being represented at the management table. A need exists for applied research and demonstration to fill the gap between plot scale research and field production. This industry-driven participatory approach similar to that of Saskatchewan and Manitoba would fill this need.

CONCLUSION

Research in the past has been developed by researchers and transferred through various extension mechanisms to the producer. This has often resulted in a top down unidirectional information flow with little input from the producers. Participatory research integrating the ideas of researchers, extension personnel and producers has shown great promise. CSIDC and MCDC are two examples of models used in Canada to encourage a participatory approach. Good success has been evidenced to date.

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LANDSCAPE IRRIGATION MONITORING

PROMOTES WATER CONSERVATION

Brent Q. Mecham[1]

ABSTRACT

A simple concept of measuring the precipitation applied to turfgrass either by rainfall or the sprinkler system is compared to ET (evapotranspiration) and reported to the turf manager. The frequent reading of the recessed precipitation gauges and reporting of the data to the turf manager allows the manager to make corrections to the irrigation schedule on a timely basis. As a result, improved water management skills have been gained.

In 1993, Northern Colorado Water Conservancy District began working with voluntary cooperators who are turf managers to determine how much water was being used for lawn irrigation. From that simple beginning, "third party" influence has been the key that has prompted greater interest in learning better water management skills and the wiser use of water resources. The voluntary cooperators have adjusted their watering schedules on their own accord, primarily because they had useful information by which they could make better water management decisions.

During 1994 the turf managers received monthly reports on the amount of water applied in inches (millimeters) compared to water need. During 1995, at the request of the turf mangers, weekly reports were generated. In 1996, the number of cooperators was increased to 22 sites and reports were created each time a site visit was made, usually two times per week.

Accountability helps prompt better performance. Although the District does not directly sell water to the end user, the fact that the District was interested in how the water was being used has caused improved performance. Conserved water and other resources have been achieved because the turf managers have made better irrigation decisions based upon useful and timely data.

SITE SELECTION

Voluntary turf cooperators were selected who had more than 10 acres (4 hectares)of turfgrass to manage. These cooperators include golf courses, cemeteries, government or school facilities, and research/ manufacturing sites. Each site uses inexpensive raw water except for one, which used municipal water.

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FIELD EQUIPMENT AND METHODS

The equipment used to monitor water usage included four All Weather Rain Gauges by Productive Alternatives, Inc. and three access sleeves made of 5" PVC well casing. Three of the rain gauges were installed in the ground in the PVC access sleeves as illustrated in Fig. 1. These gauges which are calibrated to measure .01 inch (.254 mm) of precipitation were placed in the middle of the sprinkler coverage area of the representative turf area. They were located approximately 6 feet (2 m) around the center point in an equilateral triangle pattern. Figure 2 is a photograph of the rain gauge in beside the access sleeve that is recessed approximately one-half inch (12mm) below grade so that mowing operations would not be hindered. The fourth rain gauge was mounted as a rain gauge on a post near the area being monitored.

Each cooperator helped select the spot to be monitored that would be representative of the site irrigation system. Because each site had large turfgrass lawns, large rotor or impact sprinkler heads irrigated the areas selected. Readings were taken at least weekly and twice per week during peak irrigation periods of the growing season. The recessed precipitation gauges were removed from the access sleeves, read and drained. The amounts of water were recorded and averaged for the site. The rain gauge that was located nearby was read to record the rainfall received at the site. ET calculations were derived from weather information gathered daily from a nearby weather station owned and operated by Northern Colorado Water Conservancy District. The ASCE Penman-Monteith equation was used to calculate the ET for cool season turf mowed at three inches in height.

Each week, the cooperator would receive a report indicating the accumulated ET, rainfall if any and irrigation water applied since the last time readings were taken. The need was determined by subtracting rainfall from ET. The turf manager then could quickly see if the irrigation applied matched the turf need and corrections to the irrigation schedule could be made. A sample report is shown in Fig. 3.

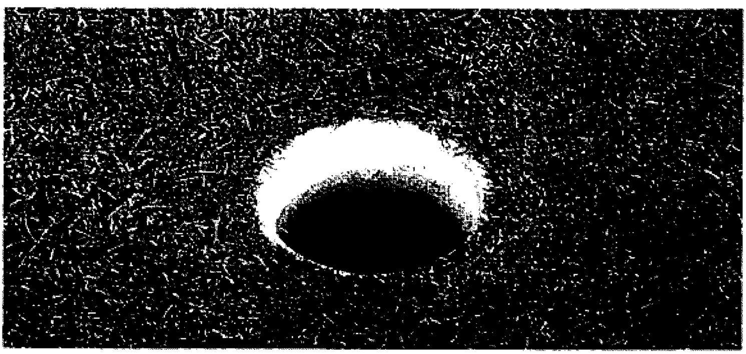

Fig. 1. PVC access sleeve in turf grass.

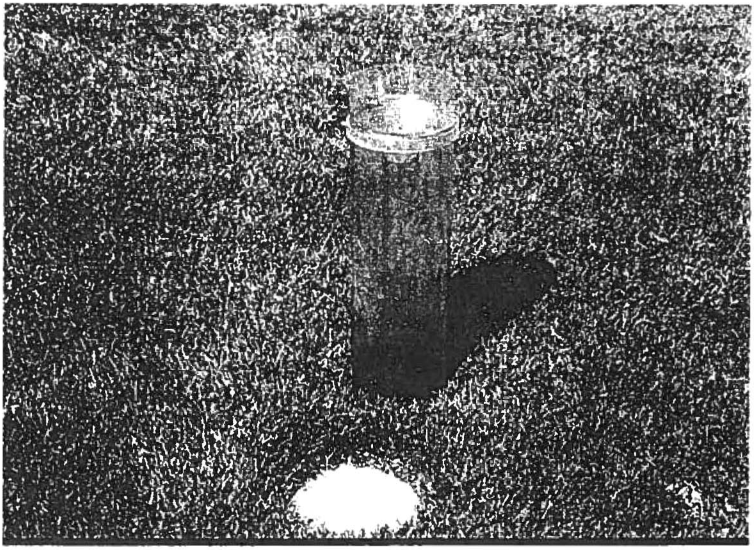

Fig. 2. Rain gauge beside a PVC access sleeve.

Northern Colorado Water Conservancy District
1999 IRRIGATION MONITORING PROGRAM

Water Usage Compared to Estimated ET

Site: Sample Report

Reading Date	Estimated ET	Site Rainfall	Water Need	Total Precip	Irrigation Applied	Excess Irrigation
14-May	1.03	0.00	1.03	0.63	0.63	-0.40
19-May	0.65	0.00	0.65	0.21	0.21	-0.44
21-May	0.28	0.07	0.21	0.23	0.16	-0.05
25-May	0.53	0.48	0.05	0.83	0.35	0.30
27-May	0.25	0.00	0.25	0.01	0.01	-0.24
2-Jun	0.82	0.21	0.61	0.65	0.44	-0.17
4-Jun	0.40	0.00	0.40	0.30	0.30	-0.10
8-Jun	0.81	0.00	0.81	0.53	0.53	-0.28
11-Jun	0.51	0.00	0.51	1.09	1.09	0.58
YTD Total	5.28	0.76	4.52	4.48	3.72	-0.80

Fig. 3. Sample Report given after each reading for the season.

RESULTS

This study began in late summer of 1993 and has been in place since. The results of the various years are indicated in the accompanying table. The numbers are indicated in percentages above or under compared to the water need. The ET was calculated for cool season turfgrass using the ASCE Penman-Monteith equation for grass that was mowed at a height of 3 inches (7.6 cm). This would represent the average height of the grass during the week if it was mowed weekly and removing only 1/3 of the leaf blade at a time. Table 1 shows during the first year the initial cooperators sites were over-watering. The following years have shown dramatic improvement in the amount of water being used for turfgrass irrigation.

Table 1.
Original Cooperators
Landscape Irrigation Monitoring
WATER USAGE COMPARED TO NEED
(ET less Rainfall)

Site:	1993	1994	1995
Cooperator-1	+60%	+3%	-3%
Cooperator-2	+28%	-12%	-33%
Cooperator-3	+22%	+24%	+13%
Cooperator-4	+59%	-2%	-2%
Cooperator-5	+51%	EVEN	+5%
AVERAGE	+44%	+3%	-4%

In 1996 the program was expanded to include more cooperators who had at least 10 acres of turfgrass under irrigation. The goal was to teach each cooperator how to obtain the ET information, monitor themselves and share that information with the water district. This has been more difficult to achieve than expected. The lack of labor resources is the reason most often given for not taking this on internally and difficulty in having internet accessibility to obtain ET information as the second reason for resisting.

Table 2 shows the additional cooperators listed for the years 1996 to 1999 showing again the comparison of irrigation water applied compared to need. It is interesting to note that in a few instances the cooperator was doing well, then suddenly was doing poorly. In those few occasions it has been a change in personnel or companies doing the maintenance, but over time the new turf manager learned to perform water management more efficiently.

Table 2.
Voluntary Cooperators
Landscape Irrigation Monitoring
WATER USAGE COMPARED TO WATER NEED

Cooperator	1996	1997	1998	1999
Cooperator - 1	29%	-24%	4%	Quit program
Cooperator – 2	-30%	-41%	-51%	-58%
Cooperator – 3	17%	-17%	21%	18%
Cooperator – 4	-38%	19%		Quit Program
Cooperator – 5	23%	4%	21%	-34%
Cooperator – 6	7%	89%	7%	8%
Cooperator – 7	36%	19%	23%	-9%
Cooperator – 8	-24%	2%	10%	3%
Cooperator – 9	-29%	-10%	-15%	19%
Cooperator –10	29%	84%	84%	Quit Program
Cooperator –11	-17%	-25%	-18%	-1%
Cooperator –12	-23%	-29%	-12%	-34%
Cooperator –13	51%	-4%	22%	33%
Cooperator –14	-28%	-44%	-32%	-42%
Cooperator –15	56%	65%	93%	62%
Cooperator –16 *	88%	-50%	3%	-13%
Cooperator –17 *	-8%	-29%	-58%	-34%
Cooperator Average	10.2%	3.6%	7.9%	-5.9%
Golf Course Average	-18.5%	-22.5%	-14.2%	-10.2%

*Cooperator 16 and 17 was the same owner, #16 is a manual system on half of the site and #17 was an automatic sprinkler system.

SUMMARY

"Third party" influence, in this case Northern Colorado Water Conservancy District, has had a positive impact to encourage improved landscape water management. Although the District has no direct authority over the water the various cooperators used, the fact that someone was interested in how they did water caused great improvement in their landscape water management. The increased awareness of proper water usage helped to actually conserve water. Besides the water being conserved, less electricity was needed for the pumping stations. Another benefit is that proper irrigation improves the quality of ground water because deep percolation and leaching of fertilizers and other chemicals are minimized.

If cost of water had been an issue, the dollar savings would have been considerable. The seventeen sites that were monitored had a combined total of approximately 750 acres (300 hectares) of turfgrass under irrigation.

Landscape water management can be greatly improved when sufficient information is provided and better water management decisions will be made. The goal is to help landscape water managers take the initiative to install these measurement devices, take timely readings, and make adjustments to their irrigation schedules on their own. When they become accountable to themselves, a great stride in responsible water management has been achieved.

We also recognize that this procedure will not work in all situations. Installation of the recessed rain gauges creates a hazard on turf where there is heavy foot traffic such as a school playground, parks or athletic fields. However there is a tremendous amount of turfgrass used for aesthetic appeal where this program will work successfully.

If nothing else, it can prompt new ideas and ways to monitor landscape water usage that will encourage improved water management skills. This procedure has been very useful to determine the amount of water being applied when a water meter is not available. Our experience has shown that turfgrass/landscape water management will improve voluntarily when timely and useful site information is made available.

UPSCALING FARMER INSTITUTIONS FOR THE MANAGEMENT OF LARGE SCALE RIVER BASINS: RESULTS FROM DISTRIBUTARY LEVEL PILOT PROJECTS IN THE INDUS BASIN OF PAKISTAN

Yameen Memon[1] Mehmood-ul-Hassan[2]

ABSTRACT

Pakistan owns the large contiguous canal network for irrigating the Indus plains encompassing an area of 16 million ha. The government has now embarked upon reforms to restructure the institutional set-up of irrigation and drainage. The major thrust of these reforms is to transfer the management of secondary and tertiary irrigation and drainage systems to the Farmers' Organizations (FOs), and also involve farmers in the decision making process at the primary level of the system. Important is that the farmers themselves have to appreciate the value of the change, take the initiative to interact with the government, and begin to play a significant role in the participatory management mode. Unless the grass-root level farmers participate in the proposed FOs, there is less likelihood for the social and financial viability of the reforms.

The experience to date with the farmers' institutions in Pakistan shows that there has been limited success in establishing functional farmers organizations even at the tertiary level of the irrigation system. A number of professionals are skeptical about the successful establishment and functioning of the proposed FOs as a large proportion of water users are socially vulnerable, politically unorganized and economically weak. Substantially skewed distribution of productive assets necessitates concerted efforts in social organization to ensure that the majority of water users are free to participate. Thus, best practices of organizational methodologies need to be followed to ensure that the reforms are implemented successfully.

The International Irrigation Management Institute (IIMI) has been involved in pilot projects for organizing farmers for Distributary management, which proved successful in organizing farmers. These organizations are now anxiously waiting for the government's response to transfer the management responsibilities to FOs. This paper synthesizes the results of the pilot efforts and suggests guidelines for

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organizing farmers at secondary levels of the canal system and upscaling these organizations to entire river basins in Pakistan.

INTRODUCTION

Pakistan's heavy investment in irrigation infrastructure has given the country the world's largest contiguous canal irrigation system. The country's gigantic surface irrigation network comprises three huge dams, 16 barrages, 12 inter-link canals, two siphons, 43 main canals, about 4,000 distributaries/ minors and more than 107,000 watercourses. The water delivery system consists of about 64,000-km length of canals to irrigate over 16 million hectares of land. Irrigation contributes towards the agricultural production, which accounts for more than 24 per cent of the country's GDP. Irrigation and drainage including the forests are equally supportive to the development of agriculture. The massive resource base of the Indus Basin Irrigation System is the cumulative effect of more than a hundred years of consistent investment in irrigation development. The high water mark of this investment was the Indus Basin Project (IBP) of the 1960s, which saw an increase in the total water supply for irrigation from about 79 billion cubic meters at the time of independence to almost 135 billion cubic meters by the end of the IBP effort (Bandaragoda, 1993:10).

The irrigation and drainage system suffers from a number of fundamental problems of which lack of beneficiary participation is one (SAR NDP, 1997). The system faces problems, such as:

- (i) Insufficient cost recovery;
- (ii) Inconsistent irrigation water supply;
- (iii) Inequitable water distribution;
- (iv) Irrational planning and spending of public expenditure on irrigation and drainage system;
- (v) Unsatisfactory planning, funding and execution of operations and maintenance (O&M);
- (vi) Deteriorating capabilities of key institutions;
- (vii) Lack of users participation;
- (viii) Poor monitoring of drainage projects and infrastructure, and
- (ix) Inadequate investment in drainage research, and failure to apply the same results to effective policy making and planning.

The Left Bank Outfall Drain (LBOD) project is one of the largest irrigation and drainage development projects in Asia (with the total cost of over 24 billion rupees) and needs public participation for operation and maintenance. The lack of participation of the community at the initial stages of this expensive project has made the take over of the project facilities by the communities much more difficult at the final stage and seems almost impossible, since they were not involved in earlier stages of centralized planning. Now a more clear and understandable strategy is needed to involve the communities for taking over the operation and maintenance of this system (Memon and Hassan, 1999).

Donors and external evaluators started to draw attention on the need to identify correct solutions to improve this state of unsatisfactory performance. Considerable performance improvement could be achieved by introducing and sustaining appropriate institutional and management innovations. Government policy levels started to participate in discussions with the donors on possible institutional reforms. Several seminars were held among local opinion leaders to discuss the implications of suggested reforms, and these ideas were later expressed in published form (Asrar-ul-Haq, et al, 1996).

Meanwhile, the World Bank (1994) proposed a reorganization of the whole irrigation sector, including the establishment of autonomous public utilities for the management (including operation and maintenance) of the irrigation water.

Currently, there is a growing awareness regarding the necessity for farmers' involvement in operation and maintenance, mostly prompted by donor concerns, and also based on the realization that declining budgetary capacities would soon have adverse effects. Yet, there is considerable pessimism among many government officials about being able to form effective farmers' organizations and their impact on the productivity and sustainability of irrigated agriculture.

Institutional Reforms in Irrigation System

Recognizing the importance of the need for change, the donors identified some important steps to be taken by the Government, including the introduction of legal reforms, as priority requirements for the launching of the new National Drainage Program (NDP). Consequently, the government initiated the enactment of Provincial Irrigation and Drainage Authority (PIDA) acts in 1997, which among other things, also provided for "encouraging the formation of farmer organizations (FOs) at the distributary level".

The four main objectives for the PIDA acts are related to: the government's new strategy for decentralizing the management of the irrigation and drainage system; the need to establish more responsive, efficient and transparent management; the need to ensure equity of water distribution and effective drainage management; and the need to introduce participatory and financially self-supporting management.

The package of institutional reforms proposed by the Government included three components: transformation of provincial irrigation departments (PIDs) to autonomous PIDAs; creation of area water boards (AWBs); at the canal level and encouraging FOs at the distributary or minor level through a pilot approach. Following this new trend, the Government of Sindh (GoS) decided to try some interventions through a few pilot projects on farmers organizations at the distributary level in areas where infrastructure development was already underway through the World Bank-sponsored Left Bank Outfall Drain (LBOD) Project in the Sindh.

Formation of Farmers Organizations

IIMI's proposal for this action research had the primary objective to test the viability of farmers' organizations managing parts of the irrigation and drainage systems so that more efficient and equitable allocation of water can be achieved. In order to achieve the objective, the pilot project aimed to conduct the following four main activities to:

(1) help establish watercourse associations (WCAs) at the watercourse level and farmers organizations (FOs) at the distributary/ minor level in the selected distributary canal command areas;

(2) educate the members of the FOs in the pilot sites for taking collective choice decisions and actions related to water resources management;

(3) assist these organizations to undertake distributary canal level water resources management on the basis of the irrigation management transfer agreement between FOs and SIDA; and

(4) identify the necessary legal and institutional support services for effectively implementing a farmer organization program on a wider scale.

Table 1 describes the basic information of the distributaries/ minors on which the farmer organizations have been formed. At the first level, watercourse associations were established at each watercourse of the distributary/minor command area involving all the land holders at the watercourse command. The members of the WCAs constituted management committee include two members of the tail and one member of less than 10 acres of land.

Table 1. Basic Information of the Distributaries/ Minors

S#	Name of Distributary/ Minor	No. of Outlets	CCA Hectares	No. of WCAs Members
1	Dhoro Naro Minor (Nawabshah)	25	5,353	463
2	Heran Distributary (Sanghar)	31	6,164	539
3	Mohammad Ali Minor (Sanghar)	10	2,020	79
4	Rawtiani Minor (Sanghar)	19	3,688	350
5	Bareji Distributary (Mirpurkhas)	24	5,728	354
6	Sanhro Distributary (Mirpurkhas)	24	6,222	295
7	Mirpur Distributary (Mirpurkhas)	53	6566	430
8	Potho Minor (Dighri)	19	3264	326

Source: Field Data Collected by IIMI Field Teams.

Main Features of the Program

Strategically, six main special features can characterize the action research program conducted to date:

(1) action research was conducted essentially in a participatory mode;
(2) replicability was the foremost consideration in pilot project implementation;
(3) equality of opportunity was provided to all water users to participate;
(4) selection of organizational leaders was effected in a truly democratic way;
(5) selection was through consensus, and not open competition; and
(6) emphasis was to form an economic organization, and not a welfare group.

The special emphasis on these features was prompted by the country's past experience in forming water users associations (WUAs) through the on-farm water management (OFWM) and command water management (CWM) programs. The largely non-democratic methods of selecting organizational leaders and the lack of long-term objective-orientation resulted in those WUAs becoming defunct shortly after the immediate objective of watercourse improvement was accomplished. The choice of watercourses for improvement through the programs had also been a subject of criticism as the decisions tended to be dominated by larger landowners.

Roles Assigned to FOs in the Reforms

- The main purpose of FOs is to benefit farmers by improving water delivery and system maintenance. Accordingly, timely access to water in dependable quantity holds the key to good performance. The FO has to prepare an action plan to conduct various activities.

- Interact with the government agencies, involve and participate in all the management activities from the planning stage itself.

- With an overall change in attitudes, the water users may be able to take a greater initiative and play a more significant role than they do now if the governments can gainfully play a more accommodating and supportive role.

- Monitor the water deliveries at the heads of distributary/ minor, outlets with the command area under the jurisdiction and control of the farmer organizations and water distribution among the members maintaining equity.

- Resolving the conflicts arising among the users in respect of water distribution ensuring equity and participation in maintenance activities.

- Coordinating and assisting the members of the management committees of different levels of farmer organizations for effectively discharging their operation and maintenance of responsibilities of the distribution system after turn over.

- Maintaining the office of the association according to the provisions in the bylaws.

Organizational Development Activities

In the organizational development process, many actors contributed. A design team coordinated the planning effort, and collaborated with the social organization field team located in the pilot sites. The selected social organizer volunteers (SOVs) and the members of field implementation coordination committee (FICC) were the other partners in the field. The SOVs were identified one/two at each watercourse level to support the field team in organizing various meetings with the water users. The FICC consisted of representatives from various agencies providing irrigated agriculture services to the farmers, including the civil administration, and selected farmer representatives.

Social organization activities were supported by some collaborative activities together with various agencies. The idea of conducting collaborative activities was to maintain the water users' interest on the action research program. IIMI played a catalyst role in bringing various line agencies and other service delivery groups to the water users on their request. These agencies included irrigation, agricultural extension, livestock and forest departments, as well as LBOD and the Water Management Component of the OFWM Directorate of the Government of Sindh. Private sector groups included Fauji Fertilizer Corporation, National Rural Support Program (NRSP) and some agricultural educational and research institutes and non-government organizations (NGOs). The overall process described above is depicted in the diagram given below.

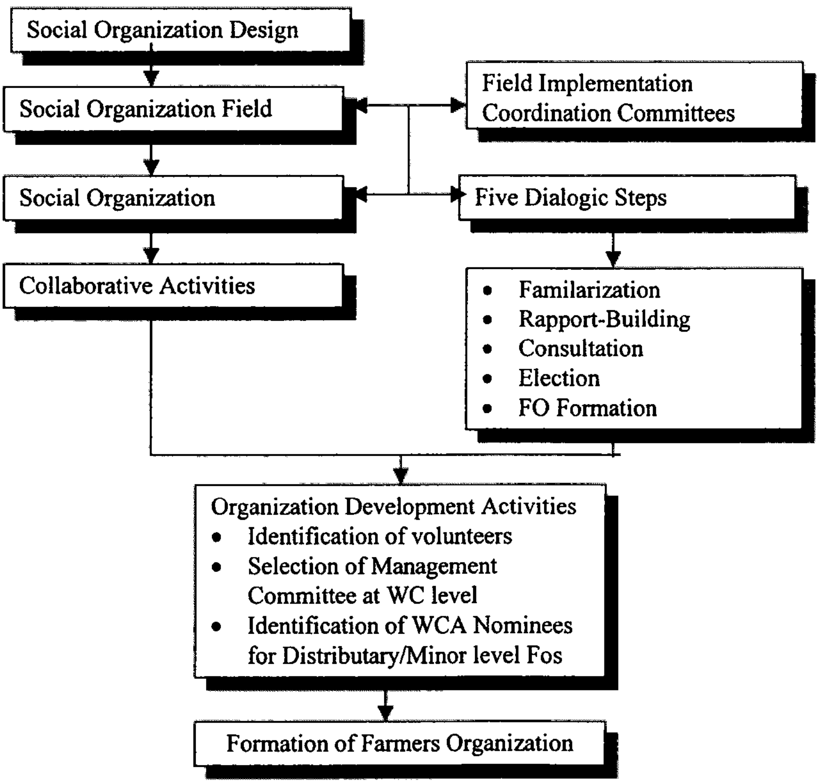

Fig. 4. Social Organization Process

Social Viability of FOs

The social viability of organizing water users in the Sindh Province is adequately proved by the pilot projects. Evidence to this effect can be seen in processes that have been completed so far.

(1) The members of the community in all of the pilot project areas were initially very reluctant to participate in any form of interactions with the field teams. This initial diffidence was transformed to a gradual appreciation of self-management and the need for getting organized and are keen to take over the distributaries from the government as fully farmer-managed systems.

(2) Socially differentiated groups, such as headend and tailend water users, large and small landowners, landowners and tenants, and influentials and vulnerable groups, have cooperated to form FOs. A democratic process for selecting the FO leaders was successfully completed.

(3) Political leaders have provided a non-partisan sponsorship without interfering in this social organization process. The acceptance of the new FOs by the community is almost 100 percent.

Demonstrated Ability for Collective Action

The collective action is more effective than individual action in sorting out social issues related to equitable resource allocation and sustainable resource management. This is particularly true for water distribution in irrigated agriculture, as irrigation systems are inherently socio-technical systems. During the canal closure periods (January-February 1997,1998 and 1999), the FOs mobilized the financial and human resources in desilting (Khati) of their respective distributaries at the pilot sites after conducting the walk-thru surveys. This activity was undertaken by the water users on their own cost during the desilting operation. FOs reflected a great deal of enthusiasm and cooperation among themselves, despite the fact that maintenance of the infrastructure was not yet their responsibility. The office bearers of FOs monitored and coordinated the entire process. A significant feature of this activity during the canal closure period was that it was an unprecedented organized behavior in mobilizing resources and attending to a well-prepared maintenance plan.

Establishing Offices and Bank Accounts

Most of the FOs initiated action to establish their offices. The FOs meetings are now being convened in these offices. The FOs have also opened their own bank accounts. The signatories of the bank accounts are the Chairman, Secretary and Treasurer of each FO. The FOs have been making consistent efforts to mobilize funds from the water user members. They formed sub-committees to collect contributions from water users by visiting them at their houses. These funds have been deposited in the bank, and the FOs are meeting their incidental expenses from these funds.

Holding of Regular Meetings

The FOs have been holding their management committee meetings regularly and engaging in broad consultation processes. This strategy has so far paid dividends as the FO members have shown some motivation to discuss various field issues and follow up on decisions taken at different meetings. The FOs are keeping their minutes of meetings and a record of their correspondence.

Membership Drive

The watercourse associations (WCAs) at the watercourse level made efforts to register the water user members of their association and obligated them to fill the membership forms. The forms are designed to provide some background information of their landholdings, tenancy status and educational level. The members include landowners, owner-operators, and lessees (in case of absentee landowners, with their approval, and their managers are included as WCA members). The management committee of the watercourse associations has decided that no person shall be excluded from the membership on the grounds of caste, creed, social group or gender. The members pay their membership fee of Rs.100/- to the association.

Network Established

Farmers make efforts to disseminate acquired knowledge and information to their members through various methods, such as delivering lecturers, discussing in the formal and informal gatherings. In addition, a quarterly newsletter has been established by the FOs in Sindhi (local) language for distribution among the members and interest individuals and organizations. The newsletter contains the decisions taken at different levels of the organization, to exchange new ideas among the members from time to time. So far two newsletters have been published and distributed.

Field Implementation Coordination Committee (FICC)

The field implementation coordination committee was formed at the field level of the project areas involving the members of FOs, officials of related line agencies, and staff of private agencies and non-government organizations as mentioned earlier. Soon after its introduction, the FICC became a convenient platform to discuss farmers' common problems related to irrigation services and agricultural production. The most important aspect of the FICC's success was that the discussions on problems were soon followed by some actions to bring the relevant services to the field. The project benefited mainly in the following ways:

- ⇨ Concept clearance of farmer-agency linkages;
- ⇨ Information transmitted to the water users by the line agencies;
- ⇨ Several collaborative activities were planned and implemented;
- ⇨ Drainage issues were openly discussed, which helped the O&M officials; and
- ⇨ Drainage and irrigation issues were seen as components of integrated water resources management.

Linkages with the Private Sector

A recent literature survey on changing public and private roles identified a growing philosophy for this "institutional pluralism" in agricultural service provision (Carney, 1998). The FOs have already started to engage in effective negotiations with private sector groups, such as input suppliers, marketing groups, and manufacturers of implements, etc. The natural development of this process, if allowed to gain root, would be to consolidate a firm commercial relationship between the private sector groups and the FOs. The latter would be willing to pay for the services that the private sector can offer in many functions, which are now inefficiently handled by the government agencies.

The traditional agricultural extension service, which was primarily a top down mode of providing instructions to the farmers, is fast becoming obsolete. Although the extension model greatly helped in the green revolution, the "after-glow" of its great success lingered on long after the necessary conditions for it have passed away (Vermillion, 1997). The threat of famine, dominant role of the government in agricultural research and extension, and large government budgets for this work, has all been diminished in size and importance. The economies of scale, facility of making quicker decisions and the articulation of internal demand, all of which are associated with well-organized farmers groups would facilitate a greater role for a demand-driven private sector irrigated agriculture advisory service. The FOs serve as the appropriate forum for many private sector goods and service delivery organizations to interact, popularize, negotiate, and market their products and services. Many pesticides and fertilizer companies have been competing for providing financial assistance to various FO activities as a strategy to attract an organized market.

Potential for Upscaling on River Basins

After completing the formation of the farmer organizations at the secondary canal level (i.e. distributaries/ minor level) there is potential to federate these organizations on the sub and main canals of the Indus river basin. In this system, not only the farmers, but other users of the water could be involved such as industries, etc. This is possible after the successful experiment of the organizations at the distributaries/ minor level.

Policy Issues

Though the government's intentions to implement reforms for up-scaling the farmer's institutions are clear, yet there are a number of policy issues yet to be addressed. These include:

- The irrigation service needs to be defined and delivered at the head of the distributary channel and the FOs need legal empowerment to distribute this water equitably among their members and assess and collect abiyana (water service fees). This embodies accountability mechanisms between the irrigation delivery agency and the FO. Unless both of them are clearly made accountable to each other, irrigation service delivery may not improve despite improving maintenance of the secondary channel

- Within the existing legal framework, the representation of the farmer organizations in the area water boards and the authority is negligible, and may lead to oversight of field concerns from policy decisions at the higher levels;

- The members of the management committee need financial and technical knowledge to manage the system. When the reforms will proceed from pilots to program scale, arrangements for the capacity-building would need to be institutionalized;

- There are several hundred distributaries/ minors in Sindh, the task of formation of FOs has to be taken over by the local institutions including non-government organizations. However, so far the capacity to organize farmers at a larger scale is limited; and

- Legal framework is under preparation since 1997. The pilot FOs have been waiting for the management transfer agreements since their formation in 1997. The long delays are impacting on FOs interest, strength, and credibility among the grassroots. The government should sign the irrigation management transfer agreement, to enable the FOs to takeover the responsibility of the distributaries/minor management. The knowledge thus created can feed into refinement of the future reform processes.

Suggestions

- The SIDA staff being laid-off under the scheme of right sizing suggested by consultants can be utilized for the formation of FOs on all other distributaries in the system. The staff can be trained to organize farmers and provide advisory services. Latter, this staff can be converted into core groups providing various services required by the FOs on payment basis. Thus, this unit will become self financing and pose no extra financial burden on the government.

- Registering the FOs and signing of the irrigation management transfer agreement within the shortest possible time on an experimental basis would boost the audacity of FOs, as well as provide useful lessons for refining the reform processes.

- Socio-technical empowerment through training the FOs would enhance the capacity of the members of the FOs to become self managing, self supporting and self financing.

- External support would also be required for a limited period to empower the FO in socio-technical aspects to achieve the financial viability and eventually sustainability, as the social viability has been proven in the pilot projects.

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EVALUATING EFFECTS OF IRRIGATION SYSTEM REHABILITATION AND MODERNIZATION BY ESTABLISHING THE WATER DEMAND MINIMUM LEVEL FOR PROFITABLE OPERATION

Ion Nicolaescu[1] Emilia Manole[1]

ABSTRACT

A large irrigation scheme having thousands of water users within its command area should be managed as an integrated agricultural production system, capable to generate economic benefits. The irrigation scheme operation intensity is variable in time, depending mainly upon the actual climate conditions and real water demand of the potential customers. This operation intensity can be expressed as the ratio between the net water volume which was applied to the crops and integrally used for increasing agricultural yield, and the net water volume required to irrigate all of the crops within irrigation scheme, calculated for 50% probability level. Evidently, there is a certain water demand minimum level of the irrigation scheme (Dmin), under which, its operation shall not be able to generate profit. In order to calculate this limit (Dmin), the authors developed a model on the base of benefit /cost analysis involving: a specific cropping pattern, irrigation water and pumping water efficiencies, economic input and output due irrigation for every crop etc. There is not any economic reason to start the operation of an irrigation scheme as long as the actual water demand level is under (Dmin) value. On such reason, (Dmin) becomes a synthetic parameter that is able to describe the technique and economic state of an irrigation system. Rehabilitation and modernization works (R&M) should influence the (Dmin) value, in a sense of its decreasing, as long as the volume of applied actions will increase. Using (Dmin) concept in a case study, for three months continuous operation time, this parameter could be decreased by seven types of R&M actions, from the actual value (45%) to the minimum one (33%).

This synthetic parameter (Dmin) seems to be a suitable and sensitive proceeding to establish the proper strategy of the rehabilitation and modernization actions for any irrigation system.

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INTRODUCTION

Irrigation practice on semiarid to humid areas has a supplemental character playing an insurance role in achieving a specific agriculture yield. The degree of using the irrigation system in such areas is very variable in time, depending on: drought characteristics (severity, duration and frequency); agriculture policy applied on local and governmental level; social and economical situation of rural people; negative impact of irrigation on the environment etc. A new situation has been created on large irrigation schemes of Romania since the law of land restitution to the former owners began to be applied. This law has generated a great number of small land users (with an average of 2.5 ha/family) inducing a lot of difficulties in relations between the O&M enterprises and the new irrigation water users. Under such circumstances, the demand for irrigation water has been decreased dramatically on the last decade and the majority of irrigation systems are operated with very low economical and technical performances. In order to avoid their operation under low performances, a model has been created to establish *the actual water demand minimum level (Dmin) for the irrigation system profitable operation* (Nicolaescu, 1998). The model could be used to solve two major aspects for any irrigation system:

- for *an efficient current operation*, the system must start to run on condition that actual water demand (D) is greater than water demand minimum level (Dmin);
- *rehabilitation & modernization works* must decrease the minimum water demand to a specific value (Dmin) depending on the technical solution types.

An irrigation system has a lot of means for R&M actions and works to be implemented in time. Applying the (Dmin) conceptual model for every technical solution or combination of them, *the proper R&M strategy* can be established for any given irrigation system, i.e. *selecting and prioritizing actions* among potential alternatives on the basis of profit assurance to the end users. In order to respect this criterion, *the real water demand of the irrigation system after rehabilitation and modernization action (D) should be greater than predicted water demand minimum level (Dmin)* evaluated by means of the proposed model. Otherwise, there will not be any guarantee to pay off the investment, which has to be done in rehabilitation and modernization works. In this context, the main topic of this paper is to show the results, which have been obtained applying the (Dmin) model to seven types of rehabilitation and modernization actions applied on a large irrigation system, as a case study.

MODEL DESCRIPTION

As has been shown (Moisa 1995, Nicolaescu 1998) the model is based on the benefit-cost ratio analysis for a given irrigation system i.e.

$$\frac{B}{C} > 1 \quad \text{.......(1)}$$

B - benefit obtained due to irrigation by selling the increment of the crops' yield (y);
C - total cost of the supplementary inputs required to achieve the yield increment.

Both parameters (B, C) are influenced by the irrigation system operation intensity or *actual water demand (D)* which is defined as:

$$\frac{V\max}{Vo} \geq D = \frac{Vr}{Vo} > 0 \quad \text{.......(2)}$$

where:

Vr – net irrigation water volume stored in the active roots depth of the crops within the system command area, during an actual irrigation season. This volume is considered to be consumed integrally by evapotranspiration, [m^3/month or season];

Vo – actual net irrigation water volume required by the crops within the same command area during the irrigation season, calculated for 50% probability, [m^3/month or season];

Vmax –(Vo) corresponding to 80% probability level, accepted on the system design phase,[m^3/month or season].

In view of the above, the actual water demand (D) is involved in the following relationships:

- *Water use efficiency in the irrigation system* as has been demonstrated (Nicolaescu 1992, 1994):

$$Es = \left(\frac{1}{Ea \cdot Ed} + \frac{Vk}{Vr} \right)^{-1} \quad \text{.......(3.1)}$$

or

$$Es = \left(\frac{1}{Ea \cdot Ed} + \frac{v_k \cdot \sum_m^n T_j}{D \cdot S \cdot \sum_m^n I_j} \right)^{-1} \quad \ldots\ldots(3.2)$$

where:
Es – overall water using efficiency of the irrigation system;
Ea – field water application efficiency;
Ed – water distribution efficiency within the irrigation plot (on farm);
Vk – volume of water that is lost along the conveyance network by seepage and operational mismanagement losses, during a defined period (month, season);
v_k – the monthly water volume that is lost along the conveyance network, considered to be constant for each month of the irrigation season (m^3/month);
$\sum_m^n I_j$ - net irrigation water demand for a specific crop on month (j) corresponding to 50% probability [m^3/ha.month(j)];
$\sum_m^n T_j$ – chronological months of irrigation system operation $\in$ [April, September];
m – the start operation month;
n – the end operation month;
j –index of the month $\in$ [m, n];
S – total irrigation command area of the system [ha].

- *Energy demand for pumping water in the irrigation system*, from the water source to the soil reservoir, E [kWh/ha]:

$$E = e_o \frac{D \cdot \sum_m^n I_j}{10^3 \cdot Es} \quad \ldots\ldots(4)$$

where:
e_o – unit-pumping energy computed as the weighted average of all pumping stations within the irrigation system [kWh/1000 m^3 of pumped water], which is:

$$e_o = \frac{\sum_{i=1}^{N}(s \cdot e_o)_i}{S} \qquad (4.1)$$

N – total number of pumping stations;
s_i – served area by "i" pumping station [ha];
$(e_o)_i$ – unit energy consumed by "i" pumping station [kWh/1000 m^3 of pumped water], calculated with formula:

$$(e_o)_i = 2{,}725 \times \left(\frac{H}{E_p}\right)_i, \qquad (4.2)$$

H_i – total dynamic pumping head [m of water column];
E_{pi} – pumping station operation efficiency.

- *Relation between the increment of the crop yield (y) and net applied irrigation water* $\left(\sum_m^n I_j\right)$ is a power function type of:

$$y = \alpha \cdot \left(\sum_m^n I_j\right)^\beta \qquad (5)$$

where:
y – is expressed in kg/ha;
α, β – are individual crop statistical parameters which have been established on the basis of research data for at least ten years of investigation, where $\beta \leq 1$. The influence of (D) on the yield increment value accepted to be:

$$y = \alpha \cdot D\left(\sum_m^n I_j\right)^\beta \qquad (5.1)$$

Economic input and output data involved in the achievement of agricultural yield increment (y), for each individual crop, are:

- Ca – total supplementary agricultural inputs induced by the technology of irrigated crop, like: seeds, fertilizer, pesticides, extra yield harvesting and transportation etc. [currency units/ha];
- Ci – O&M of the irrigation system, including water applications to the crops, not including the pumping energy cost [currency units/ha];
- C_E – total cost of energy for pumping water [currency units/ha];
- p_e – electric energy unit price [currency units/kWh];
- p_c – unit price of the crop yield sold at the farm-gate [currency units/kg].

Taking in account the involved parameters in relations (2), (3.2), (4), (5.1) and last economic data, the initial condition is rewritten as:

$$\frac{B}{C} = \frac{p_c \cdot D \cdot y}{Ca + Ci + p_e \cdot E} > 1 \quad \text{(1.1)}$$

Finally, at the limit B = C it is achieved the equation of the model, expressed by:

$$D\min = \frac{\frac{10^3}{e_o \cdot p_e} \cdot (Ca + Ci) + \frac{v_k \cdot \sum_m^n T_j}{S}}{\sum_m^n I_j \left[\frac{10^3}{e_o} \cdot \frac{p_c}{p_e} \cdot \alpha \cdot \left(\sum_m^n I_j \right)^{\beta - 1} - \frac{1}{Ea \cdot Ed} \right]} \quad \text{(6)}$$

INVOLVING THE MODEL ON REHABILITATION AND MODERNIZATION ACTIONS

It is understandable that an irrigation system becomes more efficient as (Dmin) tends to decrease. In conformity with the model expressed by function (6), this means to minimize the value of the numerator and to maximize the denominator. In order to perform, these conditions should be applied three categories of scenarios, namely:

a) *Rehabilitation an Modernization Actions* involving the following trends concerning the modification of the main parameters:

- $v_k \rightarrow 0$; $Ea \rightarrow 1$; $Ed \rightarrow 1$, for decreasing irrigation water losses throughout the entire hydraulic way in the system;
- $e_o \rightarrow$ *minimum*, for decreasing the water pumping energy consumed by all pumping stations of the system.

b) *Agroeconomical Strategy Actions* applied on the level of entire irrigation system;

- $Ca \rightarrow$ *minimum*, by practicing modern agricultural technologies;
- $\alpha \rightarrow$ *maximum*; $\beta \rightarrow 1$; $p_c \rightarrow$ *as high as possible*, by a proper actual agricultural policy especially the selection of the most efficient and adequate crops.

c) *Institutional Actions*, by promoting the farmers training and increasing the participation degree of them on all stages of the irrigation system life:

- $Ci \rightarrow$ *minimum*; $p_e \rightarrow$ *as low as possible*.

Evidently, these three categories of interventions are interrelated and are desirable to be in a full harmony among them concerning application of the (Dmin) concept. Nevertheless, the rehabilitation and modernization's works represent the most important actions to be done in achieving the maximum potential efficiency of an existing irrigation system. There is a wide range of actions to be implemented for restoration of the system to its original capability by "rehabilitation" or to exceed this one by "modernization" (Replogle, 1999).

On this reason, in table 1 are presented the most important and typical R&M actions for large irrigation schemes depending on the final goals: to save water, pumping energy and labors, and to protect the environment.

Model application to a given irrigation system can be done respecting the following conditions:

- no governmental subsidies;
- entire command area of the system is cultivated with a single crop;
- performance parameters of the system are known for actual stage and evaluated after implementation of every individual type of R&M action;
- a certain water demand minimum level of the potential users after R&M must be established.

The model has been applied to Mihail Kogalniceanu irrigation scheme that is situated on Central Dobrogea zone – one of the driest areas in Romania.

Might be Applied for the Rehabilitation and Modernization of a Large Irrigation System

ctions actions	Assessment of the principal actions	Perfor parame moc
plot (on-)	improve the water application method or replace it with a better one replace the old irrigation equipment with the modern equipment/installations adapt agricultural technologies to new irrigation method or equipment/installation practice the runoff re-use system	I
	replace the open unlined canals with buried pipes line canals control the flow rate and pressure install drainage if this is necessary	I
c convey rk	line canals replace the terminal canals with low pressure buried pipes introduction of the automatic control on the network introduce modern devices facilities to measure delivered water	
rigation m	W1 + W2	Ea,
ng stations	replace the old and used pump units with modern units decrease the hydraulic head losses introduction of the automatization proceedings on operation of pumping stations decrease the operation pressure of pumping stations in the irrigation plots	

This system is supplied with water from the Danube - Black Sea Canal by a main pumping station. Along the hydraulic open canals of the scheme, there are six repumping stations for lifting water up to the land terraces. The scheme area is divided into 33 irrigation plots, each one having its pressure pumping station. The actual data for model application are:

- S = 23,141 ha; $v_k = 7.8 \times 10^6$ m^3/month; e_o = 732 kWh/1000 m^3;
- Ea = 0.75; Ed = 0.92; Ea x Ed = 0.69; p_e = 0.055 $/kWh.

The application conditions of the (Dmin) model to this case study, the R&M types of actions and the results are presented in Table 2 and Figure 1.

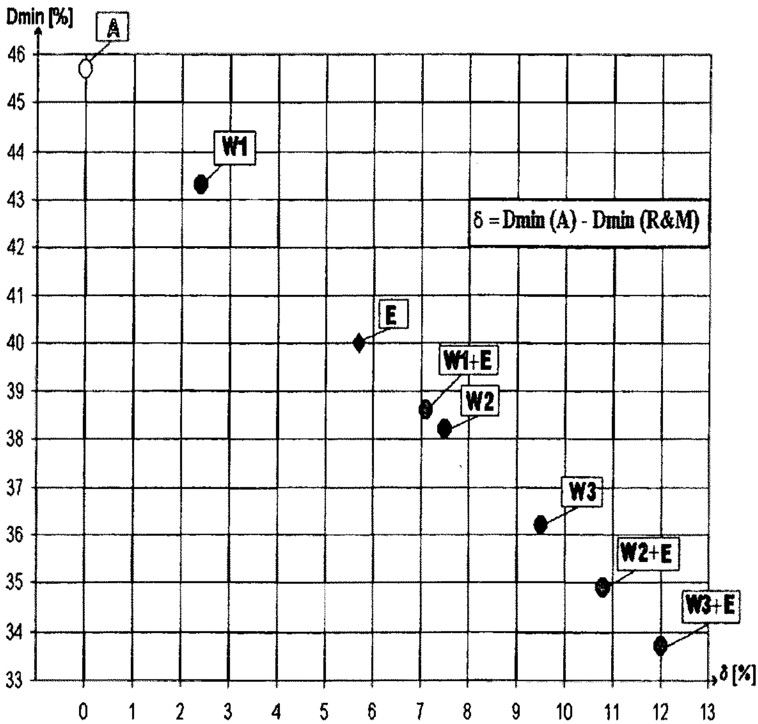

Fig.1. Decreasing Difference Rate (δ) Between the Actual Water Demand Minimum Level and Any of the Seven R&M Actions Applied to Case Study

) Model Testing and Obtained Results for Case Study (Mihail Kogalniceanu Irrigation System) T

oals of R&M actions						Actual (no R&M)	Water Saving			Energy saving	Water & Energy	
f R&M action						A	W1	W2	W3	E	W1+E	W2+E
Ea						0.75	0.90	0.75	0.90	0.75	0.90	0.75
Ed						0.92	0.95	0.92	0.95	0.92	0.95	0.92
v_k [10^6 m^3/month]						7.8	7.8	1.7	1.7	7.8	7.8	1.7
e_o [kWh/ 1000 m^3]						732	732	732	732	534	534	534
pping ern %	α	β	p_c \$/kg	Ca+Ci \$/ha	ΣI m^3/ha	Dmin (%) for T =3 months operation time:						
(b)						A	W1	W2	W3	E	W1+E	W2+E
30	81	0.55	0.103	121.31	2463	34.6	32.7	27.8	26.3	29.8	28.6	25.2
(20)	234	0.65	0.020	122.10	760	46.8	45.5	41.5	40.4	43.3	42.4	39.6
10	90	0.72	0.042	104.50	2752	14.9	14.5	11.7	11.3	13.2	12.9	10.9
5	29	0.53	0.267	118.83	1829	51.8	48.5	41.4	38.8	44.1	42.2	37.2
10	298	0.20	0.256	116.58	2100	68.5	62.1	54.6	49.5	55.6	52.2	46.8
(20)	47	0.54	0.140	115.12	700	73.1	70.1	64.5	61.9	66.2	64.3	60.2
5	55	0.74	0.156	106.05	2394	5.7	5.6	4.5	4.4	5.2	5.2	4.3
20	93	0.72	0.020	128.10	2071	50.7	47.3	41.1	38.4	43.1	41.2	36.8
as weight average of				(a)		45.7	43.3	38.2	36.2	40.0	38.6	34.9
				(b)		43.7	41.2	36.1	34.0	37.8	36.4	32.7

- actual values (A)

- modified values after R&M actions

REMARKS AND CONCLUSIONS

i. *the sort of the field crop has the highest influence on the (Dmin)* value through its profitable effect due to irrigation, i.e. potatoes and sugarbeet; grain corn and corn forage; alfalfa and soybean; sunflower and wheat;

ii. *the cropping pattern type including a large number of varied crops has a smaller influence on the (Dmin) value.* In this situation, the (Dmin) is mostly dependent by the technical and economical performances of the irrigation system. As can be noted, the calculated value of (Dmin) accordingly with the actual stage of the case study irrigation system is 43.7 and 45.7%, for two types of cropping pattern (b, a);

iii. *rehabilitation & modernization actions have a wide range of the potential effects on the (Dmin),* decreasing its values from the actual (43.7% - 45.7%) to the most efficient R&M actions (31.5% - 33.7%);

iv. according to the seven selected actions for this case study on the base of (Dmin) analyses, *the effect of R&M is increasing on the following rating*:
(W1) → (E) → (W1+E) → (W2) → (W3) → (W2+E) → (W3+E);

v. *the strategy of R&M actions is dependent above all by the guarantee of achieving a specific water demand level (D), after the implementation of rehabilitation and modernization works.* In the situation when the real (D) is less than (Dmin) specific for a type of R&M actions, the irrigation system is not capable to generate profit and the investment in R&M works could not be paid off in useful time. Under this conditions, because the actual (D) of the case study is below 25%, there is not any R&M actions economically justified to be implemented on this irrigation system. As has been previously mentioned, there are needs to increase the actual water demand (D) to the following guaranteed limits:

→ D = 40%, is able to justify the implementation of the R&M actions for:

- water saving (W2; W3) and environment protection;
- saving water and pumping energy (W1+E; W2+E) and environment protection;
- saving pumping energy (E) without protection of the environment;

→ D = 35% is capable to justify economically only two of the R&M actions (W2+E; W3+E), involving the highest values of the investment.

vi. in order to perform a specific guaranteed limit of the irrigation water demand (D) after R&M, it has to provide the institutional, social and agroeconomical policy actions which are the most suitable for a given irrigation system.

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SUBSURFACE DRAINAGE SYSTEM PERFORMANCE IN EGYPTIAN OLD LAND

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ABSTRACT

A field study was conducted at Mashtul Pilot Area MPA (260 feddans' 1 feddan = 4200 m^2) situated at north Zagazig to evaluate the performance of the long term constructed subsurface drainage system. The evaluation of grades, alignment and clogging of drain lines can give an indication of the system performance and efficiency. Three drainage units served by the same collector were selected. Four 30 m interval PVC lateral pipes were installed at different depths. The results revealed that, the collector drain slopes were either steep or flat while the overall slope of the collector drain was considered steep for about 45.50% of the sections and flat for the rest. On the other hand, some sections showed an inverse slope which can cause a decrease in the discharge rate. The regularity was classified as good for about 82% of the sections and moderate for the rest. The slope of the lateral drains was correct for 41.7% of those under study (12 lateral drains), steep for 16.60%, and flat for the rest, and the regularity was classified as poor except lateral number 71 which had moderate regularity in the first approach while, in the second approach 41.67% had moderate regularity and poor for the rest. Also the deviation of the drain pipes from the straight line was generally larger than pipe diameter. Consequently, air entrapment and sedimentation resulted. The results also indicated that, the average height of sedimentation inside lateral drains was 12.70 mm (618.30 gm/m drain length) while for collector drains, sediment was in 22.88% of pipe diameter. The average reduction in discharge capacity due to sedimentation for laterals and collectors upstream and downstream parts were 17.17%, 32.80% and 17.60% respectively. Also using Manning, Visser and Wesseling equations leads to different safety factors.

INTRODUCTION

Clogging of drains with sediment is a major factor affecting the performance of the subsurface drainage systems in areas with unstable soils. Therefore, coarser

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envelope materials made from polypropylene (PP) with pore size index (O_{90}) of about 350 microns can be recommended to protect drain tubes in calcareous soils of the Western Delta of Egypt (Omara et al. 1995). Sedimentation may also occur due to other factors such as the opening of the drain pipes, grade of the drain line, insufficient slope or water velocity inside drain pipes to remove all deposits, and also using improper type of drain envelope (DRI, 1985). Moreover, Le Grice, and Armstrong (1981) found that 91% of the examined drain pipes had slot width between 1.0 and 1.5 mm, while no slots were larger than 1.5mm. The maximum gap width between clay pipes varied greatly with 20% smaller than 1.0mm and nearly 57% greater than 2.0 mm. Also, Amer (1969) studied the relationship between sedimentation and slope of drain pipes in the Nile Delta. He found that the silt and clay deposits are found through all tile lines with different depths. The depth of deposits ranges from 10 mm (Slope 0.20-0.30%) to 40 mm (Slope 0.06%), as the slope increases silt deposits decrease. He reported that the greater depth of deposit in each tile line was found to be near the outlet (15-20m outlet). He also found that the greater part of material carried into tile lines was silt, which represents 40 to 69% of total sediments, and the rest is clay. Also, DRI (1983) reported that the silting problem is widespread in the tile drainage projects in Egypt. This problem is mainly observed with the cement pipes rather than the PVC pipes, and about 40% of the investigated laterals were completely blocked, while 40% were partially blocked. This was attributed to bad alignment, dislocation and the absence of the gravel envelope. Dierickx (1984), mentioned that the clogging of concrete laterals is more serious than of corrugated PVC laterals. This is mainly due to damaged pipes, too wide gaps, dislocated pipes, bad alignment and the absence of the gravel envelope.

Cleaning of subsurface drainage systems in Egypt was done in the past by using bamboo rods and a brush pulled though the pipes. This technique has been mostly replaced by high and medium pressure flushing machines. Routine flushing is limited to collector pipes only as most laterals lack access tubes. The cleaning of laterals through risers at the cross connectors has been tried at pilot projects. However, with good construction, flushing should not be frequently needed (Abdel Dayem, 1990). On the other hand, Van Zeijts and Zijlstra (1990) mentioned that a subsurface drainage system will function properly if it satisfies certain conditions such as no breaks or blockage in the drain lines. They also found that 6% of the newly laid drains in the Netherlands could not function properly because pipes were crushed, cracked, dented, squeezed flat, or twisted, or because connector sockets had snapped off. The main objective of this study is to evaluate the performance of the subsurface drainage system in one of the pilot areas constructed 18 years ago.

EXPERIMENTAL AREA

The study was conducted at Mashtul Pilot Area (MPA) which is located east of the Bahr Saft area, about 7 km north Zagazig. Three drainage units were chosen from Mashtul Pilot Area, namely units 7, 8 and 9 (Fig. 1). Each unit was provided with four PVC laterals. The spacing between laterals is 30 m, and has different drain depths with lateral length of 300 m. The construction of the subsurface drainage system started in December 1979 and was completed by the end of April 1980. Collector I was chosen (served 125.71 feddans) (1 feddan = 4200 m^2) throughout the course of this study. There are five sub-collectors discharging their drainage water into collector I. The design discharge rate for collectors and sub-collector in MPA was 2 mm/day. The collector drain pipes are concrete with a standard length of 0.75m and vary in diameter from 150 mm at the upstream end up to 350 mm at the outlet. Manholes were made out of prefabricated concrete units with 1 m diameter and standard length of 1 m. The design slope of laterals is 10 cm/100 m according to the Egyptian Public Authority for Drainage Projects (EPADP) standards.

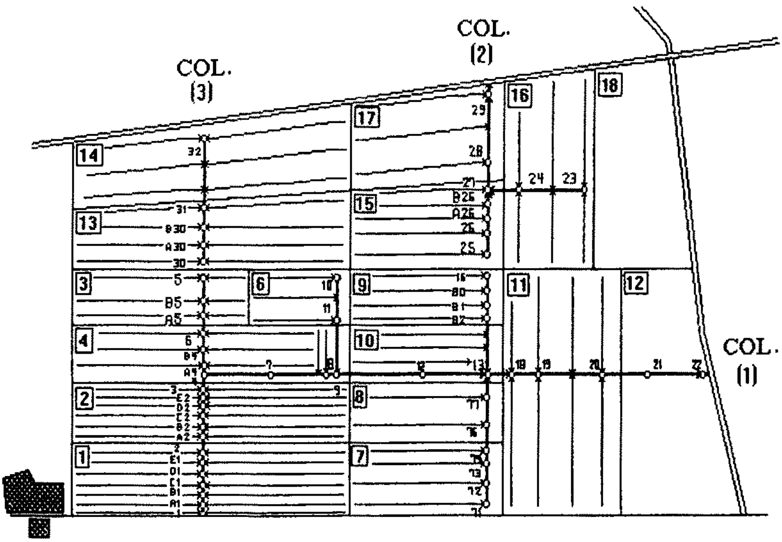

Fig. 1. Layout of Subsurface Drainage System at MPA and Drainage Units

The discharge of laterals was measured using a bucket or a cup with a known volume and a stopwatch. The time needed to fill the bucket or the cup was recorded. The volume of water discharged at the recorded time was calculated, knowing the area served by laterals under study. Moreover, the collector discharge measurements were carried out from a short rectangular steel flume which was fixed at the outlet of the collector drain. The water level in the manholes was measured daily from a fixed point using measuring tape, and the values were converted into Mean Sea Elevation. At the beginning of the study period, the backfill over the lateral pipe under study was excavated until the pipe was exposed at one point. The excavations were made at the middle of the lateral length. Part of the lateral drainpipe was cut carefully and replaced by a new one. The height of sediment (in mm) inside the drainpipe was measured. Samples from deposits inside the drainpipe were collected in each location for particle size distribution analysis using the pipette method, and for dry weight determination in grams per meter length. The soil texture is homogenous along the soil profile and the average clay, silt and sand percentages are 50, 30 and 20 % respectively. Spot levels were taken along the collector and lateral drains of units 7, 8 and 9 to evaluate the quality of construction according to the method suggested by Oosterbaan and Herrendoff (1982) as follows: The actual slope for each section has been defined as the weighted average of the actual slope according to the following equation:

$$Sa = (\frac{1}{n}) * \Sigma(\frac{H_i}{L_i}) \tag{1}$$

in which, S_a= Actual slope (m/m), H_i = difference in level between pipe at L= 0 and L = L_i (m), L_i = distance from downstream manhole (m) and n = number of levels in this section.

A parameter (U) is introduced to test the relation between the actual slope and the design one according to the following equation:

$$U = 1 - (\frac{S_a}{S_d}) \tag{2}$$

in which U = parameter qualifying the pipe slope, according to:
U < -0.2 steep, -0.2 < U < 0.2 correct, and U > 0.2 flat.

Furthermore, the deviation (d_i) from the actual slope has been calculated using the following formula:

$$d_i = H_i - S_a * L_i \tag{3}$$

in which, d_i is absolute deviation in point (i)

The deviation between the design and actual level of the drainpipe at each point is calculated according to the following equation:

$$d_i = H_d - H_a \tag{4}$$

The regularity (r) of the drainpipe is defined as:

$$r = d_{mean} + 2 * SD \tag{5}$$

in which, d_{mean} is the mean value of deviation (d_i), SD is standard deviation of (di) and r is a parameter qualifying the regularity according to: r < D/2 good, D/2 < r < D moderate and r > D poor in which D is the internal diameter of the drainpipe (m). A simple mathematical analyses was used to calculate the reduction in drainpipe area as a result of the sedimentation height inside the pipes. The equations deduced according to the method described by the Oosterbaan and Herrendoff (1982) analysis read:

$$\theta = 2\cos^{-1}(1 - \frac{H}{50}) \tag{6}$$

$$A = \frac{\theta}{3.6} - (\frac{50 \sin\theta}{\pi}) \tag{7}$$

where: θ is the center angle of sediment width, H is the sediment height (% of pipe diameter) and A is the reduction in area (% of maximum), and π = 3.1416. The reduction in discharge capacity was calculated according to Cavelaars (1985). A simple mathematical analyses was used to calculate the gap space between concrete collector drain pipes. This mathematical analysis considers the slope and diameter of pipes through calculation. The equation deduced according to this analysis reads:

$$G = 2D \sin [0.5 \tan^{-1} (i)] \tag{8}$$

Where: G= gap space (cm), D = pipe diameter (cm) and i = slope.

The safety factor can be calculated using the following equation:

$$SF = (1 - Ac/Am) \times 100 \tag{9}$$

where: SF = safety factor (%), Ac = actual command area (fed.), Am = computed maximum drainable area (fed.).

RESULTS

Quality of Construction of Drain Pipes

The evaluation of grades and alignment gives an indication of the system performance and the problems associated with misalignment such as overpressure, accumulation of sediment, reduction in discharge capacity and maintenance. The quality of construction of the drain pipes can be classified by comparing the design and the actual slope. The actual slope is an indication of the accuracy of the sight line set out by the surveyor and used by the operator to keep the trench box of the pipe laying machine on grade. The regularity is an indication of the accuracy of the operator and his capability to keep the trench box within certain limits of the sight line.

Collector Drain:

Figure 2 shows the longitudinal section of the collector drain, and the calculations for determining the qualification of the collector drain alignment are summarized in Table 1. The analysis of the collector drain slopes leads to the following results:

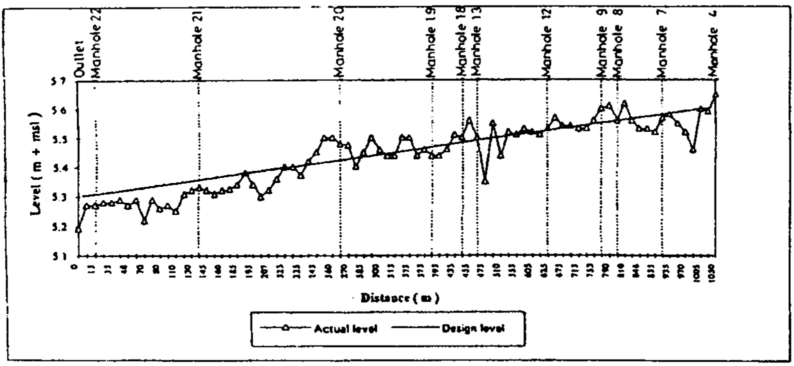

Figure 2. Longitudinal Section of the Collector System

- All sections of the drainpipe were laid at a slope, which is either steep or flat.
- The overall slope of the downstream section (between manhole 22 and 13) is steep and the upstream section (between manhole 13 and 4) is flat. However, some intermediate sections have the opposite qualification. The overall slope of the collector drain is considered steep.
- The slope of the collector sections is steep for about 45.5% of the sections and flat for the rest.
- The short section between the outlet of the collector drain and the first manhole drops sharply to the level in the open drain irrespective of the design slope.
- The section between manhole 18 and 13 is too steep. It referred to the wet condition of the soil during the construction of the pipes because the section crosses an irrigation canal and a row of trees.
- Some sections have an inverse slope, which can create problems due to the decrease in water flow.

- According to the first approach (Table 1). the regularity is classified as good for about 81.8% of the sections and moderate for the rest. The regularity of the downstream section, upstream section. and the overall collector drain has been qualified as good.
- According to the second approach, the regularity is classified as good in all except section (13-12) which has poor regularity. The downstream section is classified as good but the upstream section is poor. The overall collector drain is classified as moderate.

Table 1. Analysis of Collector Drain Alignment

Section between Manholes	Slope X 10^{-4} (m/m)		Qualification	Regularity (r) m		Regularity Qualification	
	S_d	S_a		1st	2nd	1st	2nd
outlet-22	3	40	steep	0.143	0.136	good	good
22-21	3	2.087	flat	0.089	0.053	good	good
21-20	3	2.337	flat	0.122	0.139	good	good
20-19	3	-7.599	flat	0.136	0.091	good	good
19-18	3	6.133	steep	0.102	0.048	good	good
18-13	3	20	steep	0.158	0.073	moderate	good
13-12	3	-13.603	flat	0.112	0.308	good	poor
12-9	3	3.752	steep	0.088	0.047	good	good
9-8	3	-2.222	flat	0.114	0.054	good	good
8-7	3	6.278	steep	0.08	0.113	good	good
7-4	3	-1.745	flat	0.125	0.121	moderate	good
22-13	3	4.645	steep	0.122	0.102	good	good
13-4	3	-3.085	flat	0.115	0.293	good	poor
22-4	3	4.291	steep	0.117	0.137	good	moderate

Lateral Drain:

The same analysis has been carried out for lateral drains as for the collector drain. The analysis started at 30 meters from the outlet because the lateral drain drops sharply to the level in the manhole or sub-collector. Figure 3 shows the longitudinal sections of the lateral drains for units 7,8 and 9. The calculations for determining the qualification of the lateral drains alignment are summarized in Table 2. From the results of this analysis the following conclusions can be drawn: The slope of the lateral drains is correct for about 41.7% of the lateral drains under study, steep for about 16.7% and flat for the rest. In the first approach, the regularity is classified as poor except in lateral 71 which has moderate regularity, while in the second approach the regularity is moderate for about 41.7% and poor for the rest. The deviation of the drain pipes from the straight line is generally larger than the pipe diameter. This quality of installation causes air entrapment and sedimentation resulting in pressure buildup.

Table 2. Analysis of Lateral Drain Alignment

Unit No.	Lateral No.	Slope X 10^{-4} (m/m)		Qualification	Regularity r (m)		Regularity Qualification.	
		S_d	S_a		1st	2nd	1st	2nd
	71	10	8.67	correct	0.057	0.105	moderate	poor
	72	10	1.33	flat	0.295	0.052	poor	moderate
7	73	10	10.64	correct	0.094	0.055	poor	moderate
	74	10	3.31	flat	0.117	0.235	poor	poor
	75	10	9.33	correct	0.11	0.052	poor	moderate
	76	10	9.95	correct	0.106	0.088	poor	poor
8	77	10	12.97	steep	0.138	0.103	poor	poor
	78	10	0.42	flat	0.431	0.048	poor	moderate
	79	10	14.11	steep	0.252	0.067	poor	moderate
	80	10	8.45	correct	0.232	0.12	poor	poor
9	81	10	6.8	flat	0.206	0.113	poor	poor
	82	10	7.37	flat	0.214	0.081	poor	poor

S_d:Design slope, S_a:Actual slope, r: regularity, 1st: first approach, 2nd: second approach

Clogging of Subsurface Drainage System

Clogging of drains with sediments is an important problem in the design and maintenance of subsurface drainage systems.

Lateral Drain Pipes:

The particle-size distribution of the sediments inside lateral drain pipes under study are presented in Table 3. The texture of the sediments was clay in all samples. The minimum percentage of clay was 50% which was found in laterals 76 and 77, and the maximum was 53.1% detected in lateral 73. The average was 51.5% with a standard deviation of 1.26. The maximum height of sediment was 18 mm and the amount of dry weight was 953.4 gm per meter of pipe length in lateral 73. The minimum height was 9 mm with a minimum dry weight of 390 gm per meter of pipe length. The average height of sediment was 12.7 mm. with a standard deviation of 3.6 and the average dry weight was 618.3 gm per meter length.

Collector Drain Pipes:

The section between manholes 21-20 was blocked at the beginning of the measurement season. Some tree roots were found around the nozzle of the flushing machine. During the summer season, farmers were plugging the collector and sub-

Table 3. Sediments Inside Lateral Drain Pipes

Particle size distribution	Lat. 72	Lat. 73	Lat. 76	Lat. 77	Lat. 81	Lat. 82
Clay %	51.8	53.1	50	50	52.2	52
Silt %	31.7	32.3	32.2	32.2	26.3	30
Sand %	16.5	14.3	17.8	17.8	21.5	18
Texture	clay	clay	clay	clay	clay	clay
Dry weight (g/m)	665.2	953.4	527	425.8	390	748.3
Height of sediment (mm)	14	18	11	9	9	15
Sediment height (%)	19.44	25	15.28	12.5	12.5	20.83
Reduction in area (%)	13.67	19.55	9.66	7.21	7.21	15.09
Reduction in capacity (%)	19.5	26.5	14	11	11	21

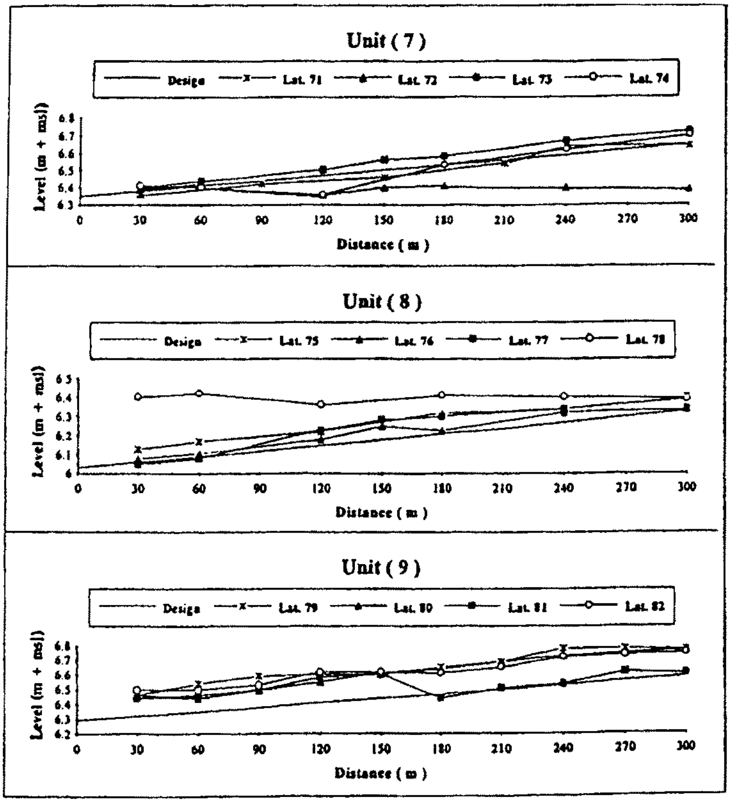

Figure 3. Longitudinal Sections of the PVC Lateral Drains

collectors D and E, Fig. 1. The amount of sediments in the manholes after the summer season was computed. The height of sediments are shown in Table 4. The maximum was 42% of pipe diameter at manhole 7 and the minimum was 5% at manhole 18. The average of the upstream section was 28.6%, but for the downstream section was 17.2%. The average sedimentation height along the whole collector length was 22.9% of pipe diameter.

Table 4. Sediment Inside Collector Drain Pipes at Manholes

anhole (No.)	22	21	20	19	18	13	12	9	8	7
Inside diameter (cm)	30	30	30	30	30	25	25	25	25	25
Sediment height (cm)	2.8	5	9.5	7	1.5	4	8.7	7	5.5	10.5
Sediment height (%)	9.33	16.67	31.67	23.33	5	16	34.8	28	22	42
Reduction in area (%)	4.7	10.96	27.19	17.73	1.87	10.33	30.95	22	16	39
Reduction in capacity (%)	7	16	37.5	24	3.5	15	42.5	31	22	52.5

Source of Sediment

Lateral Drain:

The soil in the area under study was cohesive with high clay content. It was quite stable and does not require envelope material because the stability increases with increasing the clay content (the cohesive forces exceed the hydrodynamic forces). The amount of sediments found inside the lateral drain pipes are related to unusual construction circumstances associated with the installation of drains. A common method of installing subsurface drains in Egypt is to excavate a trench, lay the drain and then backfill the trench with excavated soil. When water begins to flow, particles are carried toward the drain where they will either enter the drain or form a bridge and initiate the compaction process resulting in a stable soil above the perforation. In the case where drain openings are much larger than soil particles, sediment would continuously flow. However, the drain constitutes a confined volume which when filled can not admit more soil. The backfill should be properly compacted before irrigation water is applied to the field especially the top part of the trench. The lower part (the soil just covering the pipe) should not be compacted as it is important that this soil retains a good permeability. DRI (1987a & b) reported the results of pre-drainage investigations in MPA during the year 1978. The ground water salinity is highest in the central and south-eastern part, with a maximum value of 14.5 dS/m. The average groundwater salinity was 8.2 dS/m. The dominant salts are NaCl, $CaSO_4$ and $MgSO_4$. In the western part of the area, however, more Na_2CO_3 and Na HCO_3 occurred which indicated the possibility of an alkalinity hazard at that time. Verhoeven (1979) reported that a high salt concentration in the soil solution compresses the layer of adsorbed cations and hence physical qualities of the soil are good. After a leaching of the excess salts, the clay particles of a sodium soil disperse and fine particles may be washed down to the subsoil where they form an impervious layer. From the above, the source of sediment inside lateral drain pipes is related also to alkalinity which reduces stability after the leaching of the excess salts by drain pipes. DRI (1982) reported that some lateral drains in MPA were constructed under wet installation conditions due to irrigated fields. The wet conditions, which lower stability, can be considered as one of the sources of sedimentation in the drain pipes and will affect drain line performance.

Collector Drain:

Most of the sedimentation originated from abuse by farmers such as plugging of collectors during the rice season and surface drainage into manholes. They block the collector by primitive means to prevent excessive water losses from rice fields, which might lead to pollution of the collector. Farmers' disposal of excess surface water, by cutting holes in the superstructure of the manhole at about the level of the ground surface, usually carries substantial amounts of soil into the manhole. Also, they dump rubbish in the manholes. In addition, some manholes are partly damaged by tractors at the times of tillage, leveling and transporting of crops. In some pre-cast manholes parts of the edges are damaged which allow the irrigation water to flow carrying sediments. Bad grades with ups and downs and inverse slopes also lead to accumulation of sediment. A sudden change in the slope produces a wide gap on one side of the pipes which permits the soil backfill to enter the drain. Under certain conditions, tree roots may enter drain pipes through the gaps and subsequently grow profusely inside the pipe over considerable distances. In extreme cases the roots may fill up the entire cross-section of the pipe. These roots can be like a sieve to catch suspended materials and rubbish and accumulate sediment, and thus seriously obstruct the flow of the drain water.

Effect of Sediment on Discharge Capacity

The reduction in discharge capacity was calculated according to Cavelaars (1985). The reduction in the area curve was calculated from equations 7 and 8 but the reduction in discharge capacity curve was drawn according to Cavelaars (1985). If the percentage of sediment height reaches 40%, it means a reduction in area of 37.4% of maximum but the reduction in discharge capacity is 50% of maximum. The percentage reduction in the area and discharge capacity inside the lateral and collector drain pipes are presented in Tables 3 and 4. The maximum reduction in lateral area was 19.6% which lead to 26.5% reduction in capacity but in the collector the maximum reduction in the area was 39.9% which means 3.5% reduction in the capacity. The minimum reductions in capacity were 11% for the laterals and 3.5% for the collector. The average reduction in capacity for laterals and both the upstream and downstream parts of the collector were 17.2%, 32.8% and 17.6% respectively and the corresponding standard deviations were 6.22, 15.06 and 13.7 respectively.

Actual Safety Factor of The Collector System

A safety factor is important in the design of drainpipe diameter to compensate for a reduction in hydraulic capacity due to sedimentation or slight misalignment. The safety factors for a certain collector section have been calculated by comparing the actual command area of each section with the maximum drainable area using equation (9). The calculated safety factors of the main flow equations for drain pipes are presented in Table 5. The calculation is based on the original design slope and pipe diameters and it is assumed that the pipes have only a transporting function. The safety factors are not the same for all sections, because the required diameter, as calculated using the Manning equation, is always rounded off to the nearest commercially available pipe size. The recommended safety factor by Ven (1983) for Visser and Wesseling equations was 25% for pipe diameter 0.25-0.5 meter. For the same diameter, while Cavelaars (1985) recommended a safety factor of 40% for the Manning equation. Comparison between the recommended safety factors and the calculated ones by using Visser, Wesseling and Manning equations are shown in Table 5 and leads to the following conclusions:

- The use of the Manning equation results in the lowest actual safety factor, ranging from 20% to 42% compared to the recommended value of 40%.
- The use of the Visser equation results in the highest actual safety factors, ranging from 40% to 56% compared to the recommended value of 25%.
- The use of the Wesseling equation results in intermediate actual safety factors, ranging from 34% to 51%, compared to the recommended value 25%.

Table 5. Calculations of Safety Factor (SF) for the Main Flow Equations

Section between manholes	22-20	20-19	19-13	13-9	9-8	8-4
Pipe diameter (m)	0.3	0.3	0.3	0.25	0.25	0.25
Design slop (cm./100m)	3		3	3	3	3
Command area (fed)	125.71	112..62	99..52	62..38	57..62	56..67
Max. drainable Area (fed.)						
Visser	209.4	209.4	209.4	128.65	128.65	128.65
Wesseling	189.25	189.25	189.25	115.38	115.38	115.38
Manning	158.02	158.02	158.02	97.17	97.17	97.17
Factor of safety (%) using:						
Visser	39.97	46.22	52.47	51.51	55.21	55.95
Wesseling	33.57	40.49	47.41	45.94	50.06	50.88
Manning	20.45	28.73	37.02	35.8	40.7	41.68

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be drawn:

- The actual slope for lateral or collector drains did not coincide with the design one. The slope of the lateral drains is correct for only 42% of the lateral drains under study. All sections of collector pipe drain were laid at a slope which was either steep or flat. The regularity is classified as poor for most laterals while it was good for most sections of the collector
- The average percentage of sedimentation inside drain pipes was 17.6% of lateral pipe diameter. Consequently, this reduced the area of the lateral drainpipe by 11.8% and the discharge by 15.2%. The average percentage of sediments reached 23% of the collector pipe diameter. The average weight of wet sediments inside the manhole reached 78.8 kg. This is attributed to surface drainage or the misuse of the system by the farmers. The mobile flushing unit under high pressure was successful in cleaning drain tubes
- Regular maintenance for the subsurface drainage system is needed
- More attention should be given to the grade control and regularity of construction

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INFILTRATION GALLERIES
A VIABLE ALTERNATIVE TO "PUSH-UP" DIVERSION DAMS

F. Jeffrey Peterson, P.E.[1]

ABSTRACT

This paper deals with Infiltration Galleries as alternatives to gravel "push-up" diversion dams. The Bureau of Reclamation (Reclamation) has recently completed projects in conjunction with conservation entities and water users to demonstrate the application of infiltration galleries in rivers and streams that contain anadromous fish. The projects demonstrate that infiltration galleries buried in the stream bed can provide irrigation flows and reduce impacts to the stream, if the following three design considerations are met:

1. The intake or collection portion of the infiltration gallery is located far enough upstream as to provide the necessary head to provide for the desired diversion rate.

2. The permeability of the existing stream bed material is tested and the envelope surrounding the intake screen is composed of a properly graded gravel.

3. The system is designed with valves and bypass piping to allow isolation of portions of the collection system to allow for flow regulation and system flushing.

BACKGROUND

Partnership

Reclamation was asked by the Northwest Power Planning Council in 1991 to lead a cooperative effort with irrigators and state agencies. Irrigation water conservation demonstration projects in four areas of the Columbia River drainage were to be selected and designed. The projects were to test the "...physical, economic, environmental. and institutional viability of water conservation for improving instream flows and water quality in critical salmon production areas."

A cooperative agreement was negotiated between Reclamation and the Grant Soil

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[1] Water Conservation, Pacific Northwest Region, Bureau of Reclamation, Department of Interior.

and Water Conservation District (SWCD) for the projects developed in the John Day River Basin of central Oregon. The Grant SWCD was tasked with coordinating project activities with State and Federal agencies, local governments, interest groups and private landowners.

Problem

There are several agricultural diversion dams along the John Day River in eastern Oregon. Several of the diversions must be rebuilt every year using heavy equipment in the river to push-up the river gravels to create diversion berms. In low water years the dams incorporate several other materials to seal the gravel in an effort to create a diversion pool.

This method of diversion creates several problems. Salmon returning to spawn upriver encountered an unnatural barrier with inadequate provisions for passage. Over a given year, approximately 300 spring chinook and 1,000 steelhead pass upstream through the upper reach of the main stem of the John Day River. Because the berms are not impervious, a high structure is required to divert water at an adequate rate, and water passing through and around the berm increase downstream turbidity. Pushing riverbed materials from the upstream banks to replace the berms which washed out annually results in a wider channel at the diversion sites. Sediment deposition upstream of the berm and erosion downstream of the berm create a dynamic stream condition which results in the need for more and more berm material each year and a correspondingly higher barrier, and a shallow warmer pool upstream. With the decline of Salmon and Steelhead in the Pacific Northwest and the recent listing of Bull Trout under the Endangered Species Act, more attention is being focused on fish passage problem in rivers and streams.

PLAN

One of the planned demonstrations in the John Day Basin was to design and install Infiltration Galleries to replace selected irrigation diversions on the John Day River. The successful completion of the galleries would have several benefits: The riparian habitat would no longer be disturbed by in-river construction, fish passage would no longer be an issue, sediment load and turbidity would be reduced, the banks would be restored and stabilized, and high maintenance fish screens would no longer be necessary. Benefits to the water users would include reduced maintenance costs.

Project

Infiltration Galleries were installed at two locations in the Upper John Day Basin.

The first installation replaced an 80 foot wide "push-up" gravel dam at the L-H Diversion. Figure 1 details the basic layout and concept of an infiltration gallery.

In this installation, 12-inch diameter stainless steel well screen was used for the collector or intake pipes. The well screen was buried in the stream bed and connected to the manifold pipe which was buried along the bank of the river. Isolation valves were used to allow each collector line to be flushed out independent from the rest of the system. A bypass line, back to the river, was installed to allow regulation of the irrigation diversion. The bypass line also allows flows to return to the stream during non-irrigation periods if circulation flows are deemed necessary to keep the gallery from silting closed.

The length of each collector screen was determined using the permeability of the material in the backfill envelope, screen size opening, calculated head, and a safety factor of 2. Careful consideration is required in selecting the permeability factor as the permeability factor is on a log scale. For example choosing a permeability factor of 10 to the 3rd power for the backfill material instead of a factor of 10 to the 4th power will result in the requirement of 1,000 feet of intake screen instead of 100' of intake screen (more detailed design information is available upon request).

The L-H Diversion is located in an area of the river which had been heavily dredged for gold earlier in the century. Possible head-cutting of the river was a design concern so a sheet pile curtain was installed 30-feet downstream of the buried collectors to ensure that the stream grade remains stable. The sheet pile was installed a couple of inches below the stream bed and is only visible at the side of the river where it was keyed into each bank to prevent side cutting.

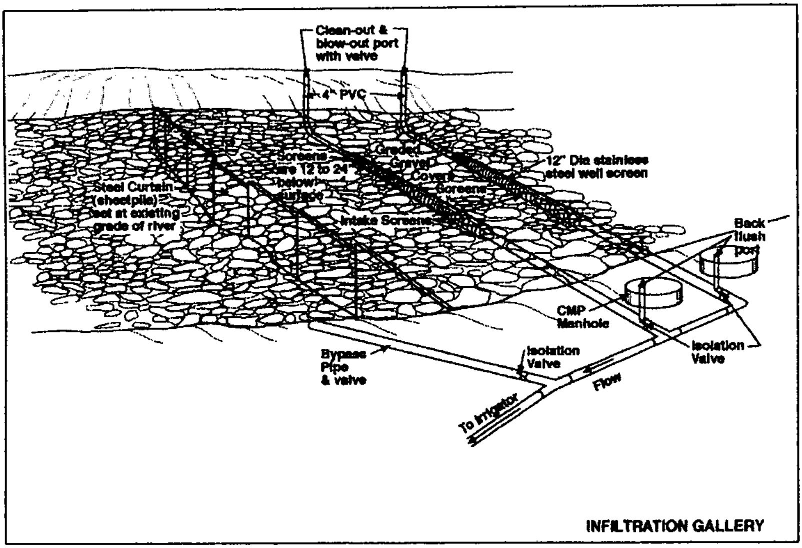

Figure 1. The Infiltration Gallery uses well screen buried in the river gravels to collect water for irrigation. A system of valves and bypass pipes allow flow regulation and system flushing. A sheet pile curtain set at the bottom of the existing river channel ensures that the well screens won't become exposed from head cutting in the river.

At the L-H Gallery 1,000 feet of 15-inch PVC pipe was installed in the existing ditch to convey the water across the dredged gravels in the flood plain. The required diversion rate at the L-H site was 1.3 cfs (cubic feet per second) which was accomplished using the collector screens and the 15-inch manifold pipe.

The second installation of an Infiltration Gallery, the Fields Diversion, was 17 miles upstream from the L-H site in an area where the river channel was more stable and only 40-feet wide. The legal diversion requirement was 1.7 cfs. Two separate stainless steel collector screens were used under the stream bed. The collectors were placed more parallel to the flow of the river because of the narrower channel. The end of the collector lines were brought into the same manhole where isolation valves and PVC risers allow each collector to be flushed independent from the rest of the system. Each collector screen was 50-feet long and backfilled with a well-graded gravel envelope. With a more stable stream bed at the Fields site, a sheet pile curtain was not deemed necessary.

Implementation Difficulties

Interest in participation in a cooperative program was initially mixed. Ken Delano, manager of Grant (County) Soil and Water Conservation District brought the potential participants together for a series of meetings. After discussions, water users decided to become partners in the program.

A standard application for the instream work was simultaneously submitted to the Oregon Division of State Lands (DSL) and the Army Corps of Engineers. This included a construction and rehabilitation plan and a firm construction timetable. DSL notified all appropriate local entities, State agencies, and interested parties of the application and requested comments. In this reach of the John Day River, Oregon Department of Fish and Wildlife (ODFW) guidelines limit stream disturbance measures to the period July 15-August 31. This is to protect adult salmon moving through the area to spawn upstream.

Coffer dams used during construction were made of stream bed material and were constructed with a backhoe. At the L-H Diversion a heavy upstream rain washed the material in the coffer dam over the installed collector screens. This material had to be excavated and removed. Ground water posed some problems but pumps were deployed and the rest of the installation went well.

Results

Fish passage is now assured at all flows. The infiltration galleries make a much smaller impact on the river dynamics than diversion berms. Heavy equipment is no longer necessary in the river. The water users can divert up to the legal water-right with less maintenance and greater ease. The Oregon Fish and Wildlife Department reaps cost savings by eliminating the need for fish screens at the gallery sites. The long term operation and viability of the Infiltration Galleries will continue to be monitored.

CONCLUSION

If sited and engineered properly Infiltration Galleries can be viable alternatives to diversion dams. Many benefits can occur for the water user and the stream ecology with the use of a low-impact Infiltration Gallery. Selecting permeability factors of the envelope material is an important step in the success of an Infiltration Gallery and should be given ample consideration in the design process. Early in the planning process all entities which have an interest in the river or water use must be contacted so that outside input and interests can be considered. This early coordination helps project managers meet the projected completion dates.

WATER QUALITY MODELLING IN DISTRIBUTION NETWORKS

Gargi Rajpara[1] Rajeev Misra[1]

ABSTRACT

A technique for the solution of unsteady flows in a multi quality water distribution system is introduced. The proposed method is compared with Preissman's scheme and dynamic analysis for water quality simulations. Each method is coupled with distribution system flow simulation model and has been used on several pipe networks of varying sizes. The front tracking method produces most accurate simulations where as Preissmen's scheme may produce oscillation. The dynamic analysis does not simulate for travel time as may be expected. However, in network simulations, with time step, larger than the longest travel time, extended period simulation may be adequate. In networks, where simulations are required at shorter time steps, front tracking method should be used.

INTRODUCTION

Development of water supply is concerned with both quality and quantity of water required to meet the needs of different zones. Neither of the factors can be neglected. Water produced in the treatment plant may be of acceptable quality, but the water reaching the consumer undergoes substantial deterioration in quality, while being transmitted through the distribution system. These quality changes are associated with complex physical, chemical and biological activities that take place during the transport process. These activities can occur in the bulk phase of water and at the pipe wall.

The movement of a contaminant in the network depends on its hydraulic behaviour and chemical kinetics of the constituent and the system. A water quality model essentially consists of (1) a hydraulic simulation model that solves for discharge in all pipes, pressure at nodes and leakage quantities and (2) a species transport model that solves for concentration of different constituents.

Water quality in a distribution system can be effectively modelled using mathematical models of water quality. Steady state water quality modelling has picked up momentum in the last two decades (*Males et al. 1985, Shah and Sinai 1988, Grayman et al.1988, Males et al. 1988, Biswas and Clark 1993, Rossman et al. 1994, Clark et al.1995, Boulos and Altman 1995).* These models assume

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complete mixing at nodes and simulate advective transport in pipes. Most of these models simulate for conservative solutes such as salt or iron concentration (*Shah and Sinai 1988*). A few models simulate the transport of decaying solutes, mainly residual chlorine (*Rossman et al. 1993, Biswas and Clark 1993*). These models have been coupled with conventional steady flow analysis models. A few attempts have been made to simulate the time-varying flow scenario by considering extended period simulation (dynamic analysis) of flow (*Males et al. 1988, Rossman et al. 1993, Rossman et al.1994, Boulos and Altman 1995, Gaikwad 1997*). In a fully transient analysis model concentration of solute is computed with an unsteady hydraulic simulation model (*Islam and Chaudhry 1997)*. A few models have been satisfactorily applied to field situations such as EPNET *(Rossman et al. 1994, Clark et al. 1995) and* dynamic algorithm of *Grayman et al. (1988).*

Most of the models are based on heuristic complex algorithms, more so for decaying solutes (*Boulous and Altman 1995, Gaikwad 1997*). At best these models can be called computational algorithms, rather solution methods. Missing sound mathematical footing carves a doubt on their applicability and robustness. The transient flow model of *Islam and Chaudhry (1997)* may produce oscillations as illustrated through the examples in this paper.

The steady and unsteady solute flow models have been formulated. The steady state solute transport model is based on analytical solution, whereas, unsteady state is simulated using the proposed method named as solute front tracking method. The results are compared with dynamic analysis (extended period simulation) and Preissmen's scheme *(Islam and Chaudhry 1997)*. Results of model application to a field situation have been presented.

UNSTEADY SOLUTE FLOW EQUATION

The unsteady unidirectional transport of solute in fluid is described by the advection dispersion equation. For a solute/ constituent with first order kinetics of reaction / decay, it is

$$\frac{\partial C}{\partial t} + V\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial^2 x} - \lambda C \tag{1}$$

Where, C = constituent concentration, V = advective velocity of fluid flow, D = dispersion coefficient, x = spatial co-ordinate along pipe axis, λ = first order reaction rate coefficient.

In the case of solute/constituent flow through pipe systems, the component of diffusion is negligible in comparison to advection and decay (Chaudhry and *Islam 1994*).

$$\frac{\partial C}{\partial t} + V\frac{\partial C}{\partial x} + \lambda C = 0 \tag{2}$$

STEADY SOLUTE FLOW EQUATION

Under steady transport of first order decaying solute in pipes, (2) reduces to,

$$\frac{\partial C}{\partial x} = -\frac{\lambda}{V}C \tag{3}$$

KINETICS OF CHLORINE DECAY IN PIPES

Assuming the reaction of chlorine in bulk flow and pipe wall is of first order, the chlorine decay constant λ in (2) depends upon many factors. These are pipe wall biofilm chlorine consumption, molecular diffusivity of chlorine in water, kinematic viscosity, pipe diameter, pipe material, flow velocity etc. (*Rossman et al 1994, Wable et al. 1991*). From field experiment and bench test data, the overall decay constant for chlorine is found to vary between 0.00049 – 0.0077 / min (*Huang and Fergen 1997)*.

KINETICS OF SOLUTE FLOW THROUGH NODES

Assuming no detention of solute at network nodes, the junction mass balance equation for the solute is,

$$\sum_{\substack{\forall\, i=\text{inflow} \\ \text{links to} \\ \text{node } j}} Q_i C_i - \sum_{\substack{\forall\, k=\text{outflow} \\ \text{links to} \\ \text{node } j}} Q_k C_k - q_j^l C_j^l - q_j^d C_j^d = 0; \qquad \forall \quad j \neq \text{Source node} \tag{4}$$

Where C_j^l= Leakage concentration, C_j^d = Concentration at demand node. Assuming complete mixing takes place at network nodes,

$$\underset{\substack{\forall\, k=\text{outflow} \\ \text{links to} \\ \text{node } j}}{C_k} = C_j^n \tag{5}$$

$$C_j^l = C_j^n \tag{6}$$

and

$$C_j^d = C_j^n \tag{7}$$

where C_j^n = concentration at node j. Using water mass balance and (5)-(8) in (5) the solute concentration within the node can be computed from,

$$C_j^n = \frac{\sum\limits_{\substack{\forall i=\text{inflow} \\ \text{links to} \\ \text{node } j}} Q_i C_i}{\sum\limits_{\substack{\forall i=\text{inflow} \\ \text{links to} \\ \text{node } j}} Q_i}; \quad \forall \quad j \neq \text{Source node} \tag{8}$$

Since, the storage of solute with in the node is ignored, the above equations apply to both steady and unsteady solute flow conditions.

FORMULATION

The objective of conventional water quality modelling is to compute solute concentration in pipes, nodes, concentration of nodal demands and concentration of leaking water. The hydraulic solutions of the system and inflow concentrations are known (Rajpara 2000).

Unsteady Solute Flow

For a typical pipe network (Fig. 1) with P pipes, and N - M nodes, the objective is to compute P concentration in pipes; N - M nodal concentration, N - M concentrations of demanded water and N - M concentration of leaking water from nodes. In all, P equations for pipes of type (2), N - M nodal mass balance equations of type (4), N - M nodal equations of type (6) and (N - M) concentration equations of type (8) are solved for P + 3 (N - M) above unknown concentrations at pipes and nodes. Since, unsteady solute flow in pipes is represented by a differential equation of unknown analytical or closed form solution, the unsteady water quality analysis requires use of numerical techniques. Implementation of these numerical techniques often requires descretisation of an individual pipe into a number of sub-reaches/nodes as discussed in subsequent section. This does not alter the above formulation, since the inner descretisation of pipes results in as many additional unknown concentration values at inner grid points, and as many number of difference equations of (2).

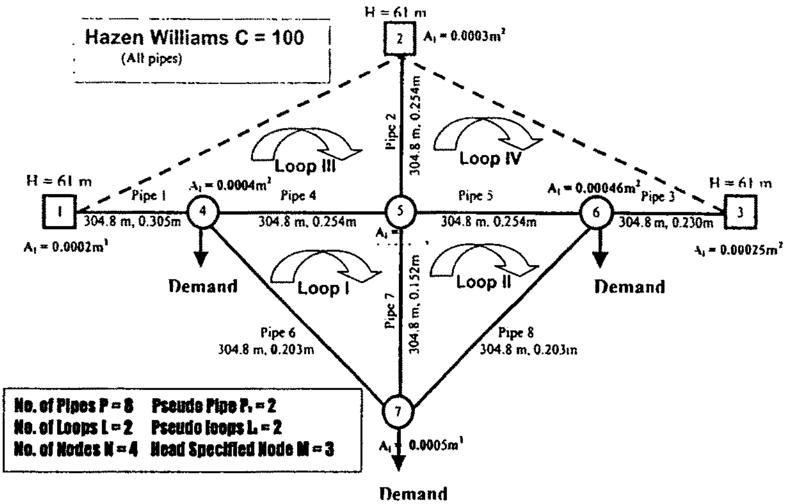


Fig. 1. Definition Sketch of Study Network

Steady Solute Flow

For a typical pipe network (Fig 1), P solute flow equations for pipe (3); N - M nodal mass balance equations of type (4), N - M nodal equation of type (6) along with N - M equations of type (8) are solved for P pipe concentrations; N - M nodal concentrations; N - M concentration of demanded water and N - M concentration of leaking water from nodes. Depending upon the analysis methods, accuracy constraints may require descretisation of links into a number of grid points. Each such addition of a grid point would result in one additional unknown and one additional difference equation of the method chosen. This completes the formulation.

Steady Solute Flow Analysis

For a steady flow condition, the analytical solution of steady flow equation is,

$$\frac{C_g}{C_{g-1}} = e^{-\frac{\lambda \Delta x}{V}} \tag{9}$$

where C_{g-1} = concentration (mg/l) at grid point g-1; C_g = concentration (mg/l) at grid point g. This analysis is used to set the initial condition for unsteady solute flow simulations.

Unsteady Solute Flow Analysis

Preissmen's Scheme: In this method the differential equations for solute flow (2) are directly solved using finite difference approximations. Several finite difference numerical schemes are available to solve the set of equations. However, the Preissmen implicit scheme of Islam and Chaudhry (1997) is chosen for comparison. In this scheme the derivatives are approximated over the grid points as

$$\frac{\partial C}{\partial t} = \psi \frac{C_{g-1}^{t+\Delta t} - C_{g-1}^{t}}{\Delta t} + (1-\Psi)\frac{C_{g}^{t+\Delta t} - C_{g}^{t}}{\Delta t} \tag{10}$$

$$\frac{\partial C}{\partial x} = (1-\theta)\frac{C_{g}^{t} - C_{g-1}^{t}}{L} + \theta \frac{C_{g}^{t+\Delta t} - C_{g-1}^{t+\Delta t}}{L} \tag{11}$$

$$C_p = \psi\left[\theta C_{g-1}^{t+\Delta t} + (1-\theta)C_{g-1}^{t}\right] + (1-\psi)\left[\theta C_{g-1}^{t} + (1-\theta)C_{g}^{t}\right] \tag{12}$$

where θ and Ψ = weighting parameters in the temporal and spatial directions respectively. Substituting these in (4.2) and simplifying,

$$a_1 C_{g-1}^{t+\Delta t} + a_2 C_{g}^{t+\Delta t} + a_3 C_{g-1}^{t} + a_4 C_{g}^{t} = 0 \tag{13}$$

where

$$a_1 = 1 - \psi + \alpha\theta \tag{14}$$

$$a_2 = \psi - \alpha \ldots \theta + \lambda \Delta t \Psi \theta \tag{15}$$

$$a_3 = -1 + \psi + \alpha(1-\theta) + \lambda\Delta t(1-\psi)(1-\theta) \tag{16}$$

$$a_4 = -\psi - \alpha(1-\theta) + \lambda\Delta t\left[\psi(1-\theta) + \theta(1-\psi)\right] \tag{17}$$

where $\alpha = V(\Delta t/\Delta x)$= Courant number.

Front Tracking Method: In the above method, concentration at fixed grid points are obtained at all time steps. However, in this method, the movement and position of the solute front is traced along the individual pipe length. Hence, except at upstream and downstream ends of a pipe, the solution in a pipe is not performed at a fixed location.

Since, solute diffusion is ignored in this analysis, a solute mass travels with in a pipe at velocities equal to that of fluid motion. In this paragraph, the proposed method is first described for conservative solutes. In subsequent paragraphs, the method is extended for decaying solutes. Motion of the solute front with in a pipe can be treated as series of solute fronts as in Fig. 2. Let the position of various solute fronts at different t be known. The average velocity of fluid between t and t + Δt is V_1. Hence, every lump of solute in a pipe would propagate a distance of $dx_1 = V_1\Delta t$ during this period. The new position of each such solute front can be obtained by simply adding this incremental distance to their respective previous positions. Similarly, in the next time step, the new incremental position of the solute fronts are obtained as $dx_2 = V_2\Delta t$. The new location of individual fronts are obtained. This procedure is continued until any given solute front crosses the pipe. Within this duration, the position of solute lumps that enter the pipe between time step t + (n - 1)Δt and t + nΔt also get added. The method can be best described through Fig. 2. An inflow solute hydrograph of Fig. 2 is tracked through a pipe.

The above tracking algorithm can be directly modified for decaying solutes. Apart from simply locating the new position of a given front, its decayed concentration is also computed. The algorithm is described through a definition sketch of Fig. 2. The solute fronts of Fig. 2 are tracked over the next time step Δt. The solute mass not only moves by a distance $dx_1 = V_1 \Delta t$, but also decays at a rate $e^{-\lambda\Delta t}$ (multiplicative) during this period i.e.,

$$C_{nf}^{t+\Delta t} = C_{nf}^{t}\, e^{-\lambda\Delta t} \tag{18}$$

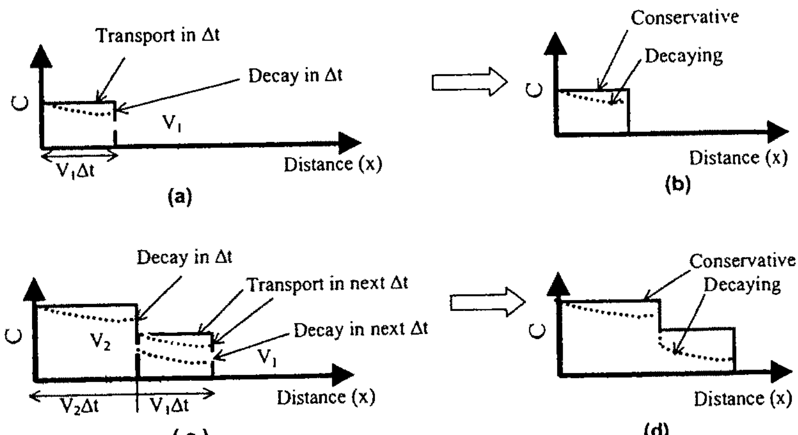


Fig 2: Definition Sketch for Front Tracking Method: Firm Lines Represent Transport of Conservative Solute and Dotted Lines Represent Transport of Non Conservative Solutes.

where C_{nf} = concentration of n^{th} solute front. The concentration profile at time step $t + \Delta t$ is shown in Fig. 2b. Similarly, between time steps $t + \Delta t$ and $t + 2\Delta t$, the solute front moves a distance $dx_2 = V_2\ \Delta t$ and decays further. The new solute concentration profile is shown in Fig. 2c. Similarly, the new position of solutes entering the pipe with in time t and $t + \Delta t$ can also be traced for subsequent time steps as shown in Fig. 2d.

Extended Period Simulation: As mentioned earlier, the unavailability of transient water and solute flow models for pipe networks has forced modellers to use steady solute and flow models to simulate the effect of hourly variations in concentration. A few improvements such as procedures to incorporate the time variations in concentration at inflow nodes have also been put forward. These are often known as extended period or dynamic analysis of the system. In this approach, steady state of flow is assumed at every time step, so that the steady flow models can be used.

RESULTS AND DISCUSSION

A simple hypothetical unsteady solute flow situation has been designed to establish the correctness of unsteady water quality analysis methods. Unsteady solute flow conditions arising due to variation in concentration of solute at inflow nodes of study Network in Fig. 1 are simulated. The data for the study network is given in Fig. 1. The steady flow conditions are assumed throughout the simulation. The concentration of chlorine at source nodes 1 and 2 is varied gradually, whereas the concentration at source node 3 remains unchanged throughout the simulation. Results are non-dimensionalized with respect to initial concentration (t = 0 sec) at source node 1. The unsteady solute flow condition occurs due to variation in inflow concentration at source nodes. The chlorine concentration at node 1 remains at 1.0 for the first 4000sec of simulation. It is gradually increased to 1.5 in next 8000 sec and remains at 1.5 after 12000 sec. Similarly concentration of the source node is not changed for the first 4000 sec. In the next 8000 sec, it gradually increases from 0.8 to 1.2 and remains unchanged after 12000 sec. The concentration of solute at source node 3 (Fig. 1) is maintained at 0.8.

Effect of Time Step

The above transient chlorine flow situation is simulated using different time steps. Results for the Preissmen scheme are compared in Fig. 3 whereas Fig. 4 compares concentration hydrograph for the Front tracking method. The Front tracking methods exhibit slight lag for different time steps. The Preissmen schemes exhibit negligible lag with increase in time step, but produces an oscillatory concentration hydrograph for all the time steps considered.

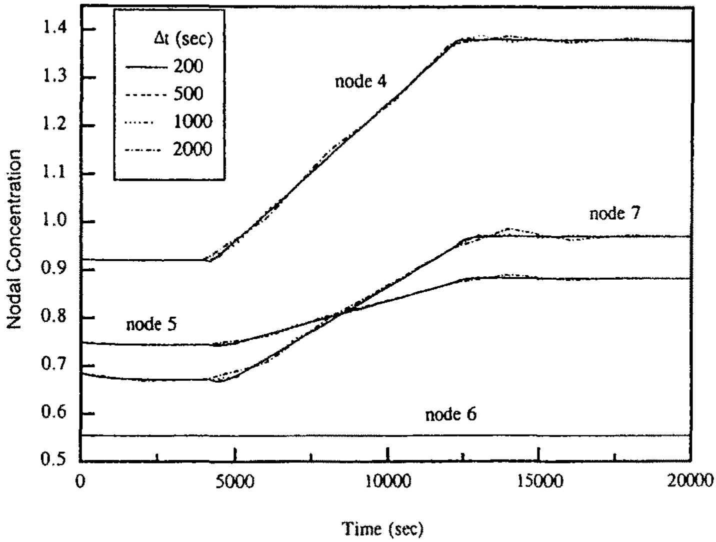


Fig. 3. Effect of Time Step on Preissman Scheme.

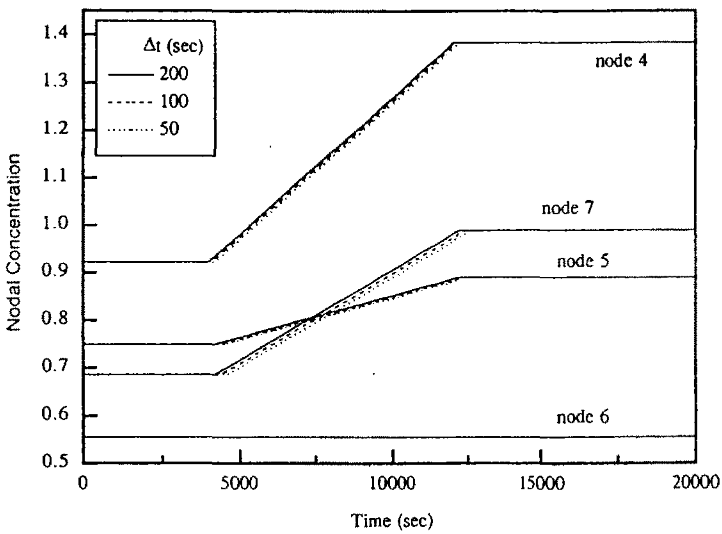


Fig. 4. Effect of Time Step on Front Tracking Method

Comparison of Methods

The results of Preissmen's scheme, front tracking method and dynamic (extended period simulation) analysis are compared in Fig. 5. The results of extended period simulation do not exhibit the effect of travel time as may be expected. The results of Preissmen's scheme are not accurate. The front tracking method produces the most accurate simulations. However, in network simulations with time steps larger than the longest travel time, extended period simulation may be adequate. In networks where simulations are required at shorter time steps the front tracking method should be used.

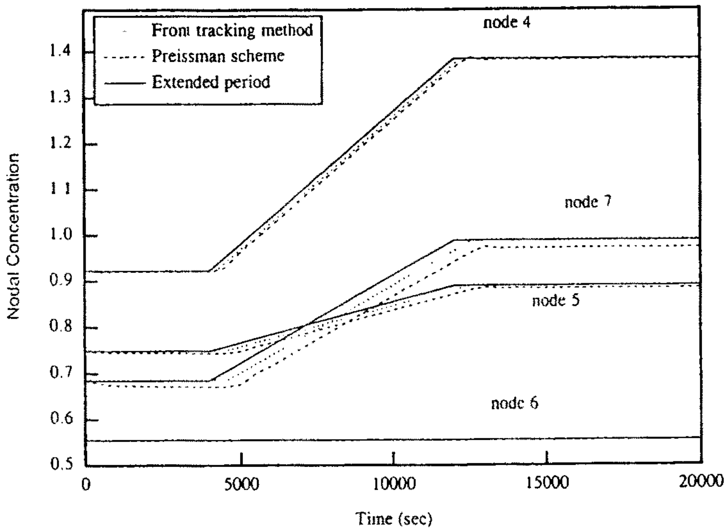
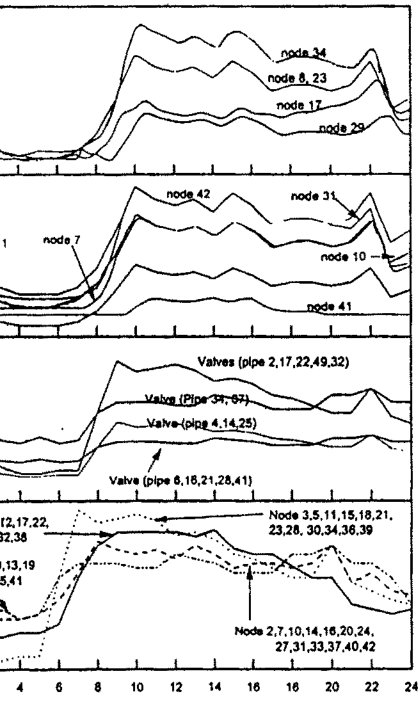


Fig. 5. Comparison of Methods

APPLICATION

The above mentioned water quality analysis is applied to a moderately large water supply network of the residential colony of Anapara Thermal Power Station in Uttar Pradesh, India. The modelled network constitutes of 42 nodes, 53 pipes, 3 overhead tanks and 3 direct pumping stations. The chlorine with the decay constant of 0.000277/sec is considered as non-conservative solute. The water quality performance of the network under unsteady flow conditions of flow and solute transport is evaluated over a period of 24 hours. Daily operation of butterfly valves in pipes 2, 4, 6. 14, 16, 17, 21, 22, 25, 28, 32, 34, 37, 41 and 49 are presented in Fig. 6. Daily variations in inflow concentration of nodes are presented in Fig. 6. Results for transient flow situation are presented in Fig. 7. Results of water quality simulations by considering both conservative solute and



ariation of (a) Nodal Concentration, (b) ode Concentration, (c) % Valve Opening ow Demand Load Factor for 24 hours

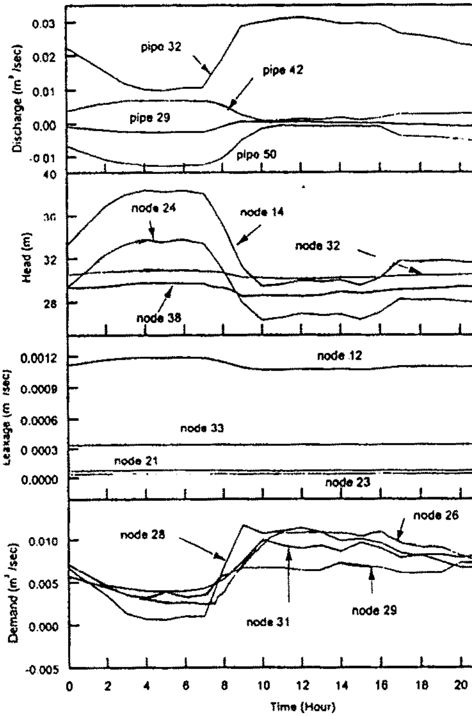


Fig. 7. Variation of (a) Pipe Discharge, (b) Head, (c) Leakage and (d) Demand for 24 hours

residual chlorine are presented in this section. The concentration values are non-dimensionalised with respect to inflow concentration at node 1. Due to storage time considerations the concentration of inflow from overhead tanks at nodes 7, 31 and 41 remain the same as that of the detained water in overhead tanks i.e. 0.9, 0.8 and 0.7. For the duration the overhead tanks were being fed by the network, the water quality of the feeding water was same as of water at those nodes. It should be noted that, even when the overhead tanks were feeding the network, the flow in some of the pipes connected to the overhead tank nodes was towards the overhead tank. As a result mixing of waters from over head tanks and inflow pipes takes place. The concentration at the overhead tank nodes is significantly different from the concentration of water coming from overhead tanks as seen in Fig. 6. Typical concentration hydrographs at five nodes are presented in Fig. 6. The shape of the concentration hydrographs at other nodes and inflow are almost the same, except for a lag due to travel time considerations. However, the mixing and/or decay significantly changes the magnitude of concentration values. The nondimensional concentration contours at every 8hrs and 20hrs are also presented in Fig. 8. Nodes having the least residual chlorine concentration are marked as critical nodes. The location of the critical node and magnitude of least residual chlorine concentration changes from time to time are seen in Figs. 6 and 8. Hence, for practical applications, identification of the critical node based on average daily demand or one demand may be erroneous. The node 26 that caters to the school has been marked as node of interest. The simulated results exhibit a considerable change in residual chlorine concentration.

CLOSURE

The mathematical formulations and models for steady and unsteady conventional analysis are presented. Convective transport of decay in constituents is considered. Unsteady flow models, namely Front tracking and Pressiman scheme and Extended period simulation, are developed. The unsteady flow models are compared for test cases that are suitably designed. Results, for both decaying and non-decaying solutes, under steady and unsteady flow condition for the network of township are presented. Preissman's scheme exhibits oscillations.

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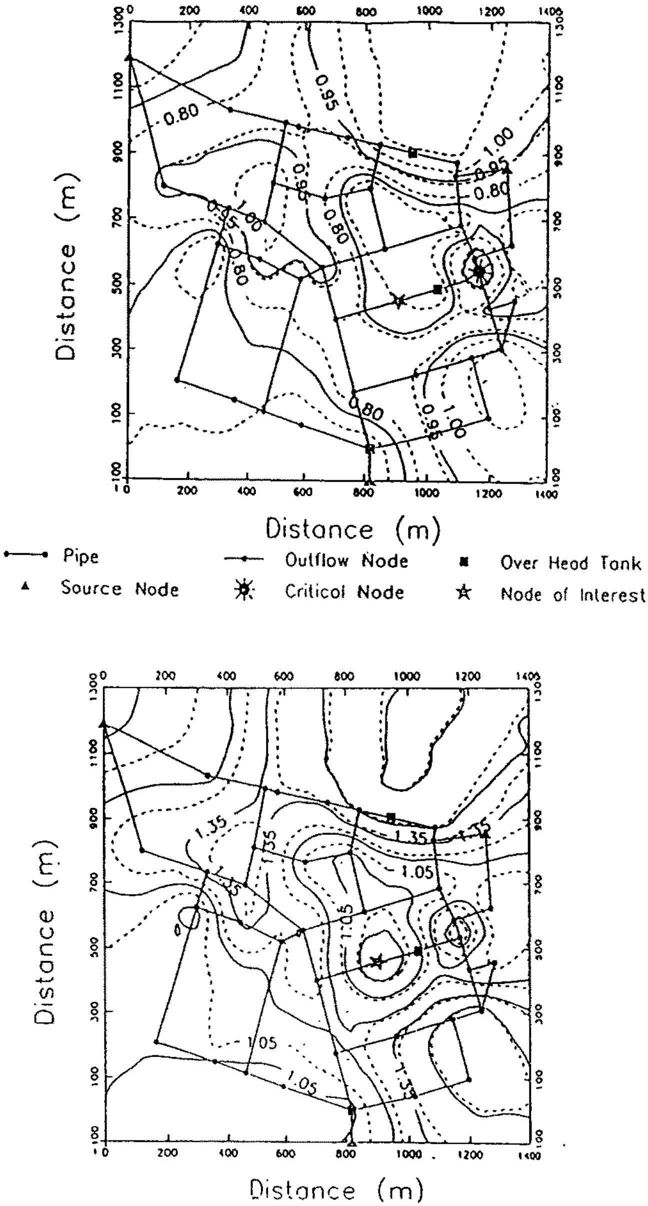

Fig. 8. Comparison of Concentration Contour for Conservative (firm line) and Non Conservative (dot line) Solute at (a) 8hrs. and (b) 20hrs.

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TESTING OPERATIONAL PERFORMANCE OF A PRIMARY CANAL USING HYDRODYNAMIC FLOW MODEL DURING DESIGN STAGE

Saeid Khalaj Savojbolagh [1]

ABSTRACT

The Shafarud Irrigation Project is located in the North Western part of Iran by the Caspian Sea. At present, traditional water courses are irrigating about 7,150 ha of paddy fields. Even though there are water shortages during low river runoff and peak growing season, it was decided to extend the area under paddy to about 12,300 ha in net. This is not possible without taking full advantage of the river runoff, and preventing the flow of a large volume of water to the Caspian Sea annually. Therefore, it was foreseen to construct a storage dam on one of the four rivers existing in the area, and three diversion dams on the other rivers. By taking full advantage of the river runoff through the diversion dams and provision of irrigation water during deficiency period from the storage dam, the goal can be achieved.

The objective of this paper is to describe the design methodology adopted for the Shafarud primary canal by taking into account the operational performance of the system by using the MODIS hydrodynamic flow model. In the design of new primary canal, it was decided to investigate the effect of manual operation of secondary offtakes and impact of river runoff variation in two alternatives of automatic upstream and self-regulating downstream control systems during deficiency and sufficiency river runoff periods.

The results of the simulation show that the unsteady flow phenomena has an important effect on the water delivery and operational efficiency of the system, specially in the case of alternative using an automatic upstream control.

It was noticed that management by automatic upstream control is difficult, and during sufficient river runoff relatively more flow should be released from the storage dam as compared with its variant alternative of self-regulating downstream control system but due to topographical condition of the canal alignment with a few modifications it was considered to be a better design option.

The idea of taking into account the operational performance of a new irrigation system at the time of design is becoming increasingly important every day,

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especially when it is realized that many old irrigation schemes do not function properly. One of the main reasons is that water distribution and unsteady flow conditions were hardly considered in their design.

THE PROJECT DESCRIPTION

The present devices for distribution of irrigation water in the area are primitive and the water distribution method is more dependent on the visual inspection. In spite of great attention given for equitable distribution of water among the traditional irrigation ditches, in practice the method for distributing irrigation water is the least accurate.

Due to non-existence of permanent distributors, a large number of man-hours are required to carry out an accurate distribution of irrigation water.

Although the soil and water resources are reasonably rich to increase the area under paddy fields, irrigation water shortage and scarcity is a normal occurrence even for the present area under irrigation in the months of peak crop water requirement because the overall irrigation efficiency is very low. So it is envisaged to put a new modern and efficient irrigation network in place in the project area.

Objective

The objective of this study is to design Shafarud primary canal, taking into account the operational performance of the system, using MODIS hydrodynamic flow model.

Water delivery schedule

A fixed and rotational water delivery schedule to tertiary offtakes, resulted in variable (from 50 to 100%) and continuous water delivery to secondary offtakes. Two important occasions from paddy growing season were picked out, one during high river runoff (in the month of May) called it sufficiency period, and the other during low river runoff (in the month of July) which is called deficiency period.

In the following figure (Fig. 1) of water delivery schedule to secondary offtakes, states 1 and 2 occurred in sufficiency period, while states 3 and 4 take place during deficiency period.

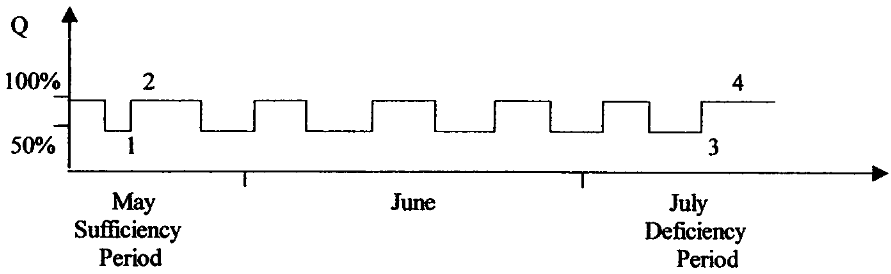

Fig 1. Water Delivery Schedule to Secondary Offtakes

SELECTED PRIMARY CANAL (SR)

The right primary canal (SR) of the Shafarud which is connected to the storage dam (SD) and two diversion dams (DM1 & DM2) was selected for investigation. Fig. 2 & Fig. 3 are present flow direction during sufficiency and deficiency periods respectively.

As can be observed from these figures, during sufficiency period there should be almost zero discharge in reaches AB and CD, because the rivers' runoff is high enough to satisfy the irrigation water requirements of the related secondary offtakes.

On the other hand during deficiency period more water should be released from the storage dam (SD) in order to compensate the deficiency of river runoff for secondary offtakes no. 3, 4, 5, 6, and 7.

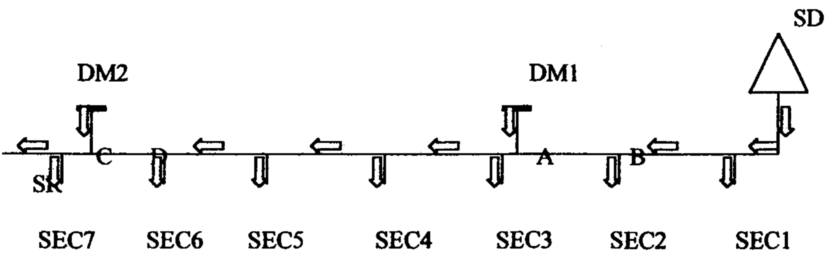

Fig. 2. Flow Direction During Sufficiency Period

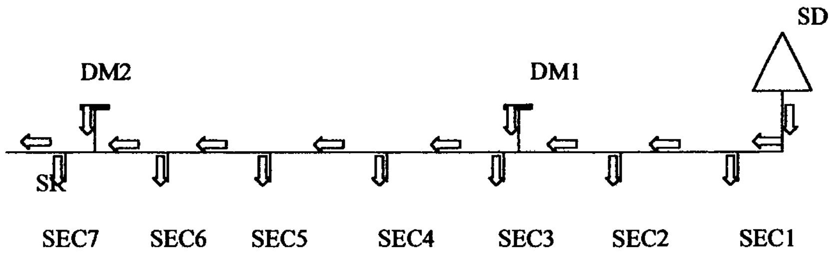

Fig. 3. Flow Direction During Deficiency Period

Flow control system

Two different alternatives for flow control system were considered for SR primary canal. The first one was an automatic upstream control, and the second one was self-regulating downstream control.

Water supply strategy and operation

In the case of first alternative of upstream control system in the main, primary and secondary canals, the water supply method to the secondary offtake is on a semi-demand basis.

A large Water Operation Centre (W.O.C.) [3] is required to instruct and supervise every regulation and adjustment to be carried out by gatekeepers on offtakes at diversion dams, secondary, and tertiary offtakes throughout the whole irrigation network. The tasks to be performed by the Water Operation Centre are as follows:

- Data collection on crop stage;
- Collection of meteorological data;
- Determination of water need for tertiary units;
- Assessment of water availability;
- Calculation of flow through each reach; and
- Determination of gate setting;
- Information to ditch riders;

In second alternative of self-regulating downstream control in the main (coming from storage dam) and primary canals, the system is decentralised and the water supply method to secondary offtake is on demand basis.

It means that the numbers of water operation centres are equal with the number of seconday canals (each secondary canal has its own water operation centre) but it is obvious that their staff requirements are much less than the first alternative.

In the first alternative of automatic upstream control, a Duckbill check structure was selected as the water level regulator just downstream of each secondary offtake.

Design of SR primary canal

A Duckbill check structure was considered appropriate as water level regulator in first alternative of automatic upstream control. In order to minimize the water level variation in front of offtake, appropriate length of the Duckbill check structure was selected but on the basis of economic justification [4].

For managing a constant flow delivery to secondary canals during either maximum or minimum flow through the primary canal, double baffle Neyrpic modules was selected as secondary offtakes. In automatic upstream control, the sill level of the Neyrpic module was fixed at a certain depth (0.51 and 0.28 metre for "L2" and "XX2" types respectively) lower than halfway between maximum and minimum water levels in front of the offtakes.

In the second alternative of self-regulating downstream control system just (or in vicinity) upstream of offtake, an Avio gate was selected as water level regulator.

For comparison with the first alternative, the same type of double baffle Neyrpic modules was selected as secondary offtake. Sill level of the offtakes are positioned at a two different depths (0.51 and 0.28 metre for "L2" and "XX2" types respectively) lower than design head (target level) of Avio gates. After structures for both alternatives of automatic upstream control, and self-regulating downstream control system for the SR primary canal were finalized, now it was possible to draw the longitudinal profiles of the canal for both alternatives. The following steps were carried out in order to calculate the water line (FSL) and preparing the longitudinal profiles of main and primary canals:

The longitudinal profile of SR primary canal (16.19 km long) was prepared with horizontal and vertical scale of 1:25000 and 1:100 respectively;

Locations of all secondary offtakes were shown on the longitudinal profile;

Taking into account number of tertiary units located downstream of each secondary offtake, and considering 90 % conveyance efficiency from tertiary offtake up to the headwork, capacities of canals were calculated;

The minimum water levels were established to command the land for irrigation;

All canals were envisaged to be concrete lined in the Shafarud project area;

With adopted design criteria and by using the Manning Formula, parameters of the canals cross-sections were calculated for each reach;

Bottom width, side slope, manning coefficient used in design of primary canal were 1.5 metre, 1.5 (H:V), and 0.014 respectively. Bottom slope of the primary canal is 0.5 metre per one kilometre (1/2000);

Taking into account the calculated head losses due to regulating structure (Duckbill for automatic upstream control and Avio for self-regulating downstream control), normal depth of water, length of selected reach (especially in second alternative) and full supply line are drawn;

Natural ground surface is about 1.0 metre above bottom slope of SR primary canal and very much parallel to it.

Following completion of the designs, the effect of manual operation of secondary offtakes and changes of river runoff in two alternatives of automatic upstream and self-regulating downstream control systems during deficiency and sufficiency periods was investigated.

In both alternatives, offtake setting were changed from 50 to 100% position manually according to time schedule.

Four alternative situations of automatic upstream control during sufficiency and deficiency periods, and self-regulating downstream control system for the same periods of sufficiency and deficiency by using MODIS hydrodynamic flow model [7] were simulated. Operation performance parameters have been formulated. The two performance parameters of delivery performance ratio (DPR), and operation efficiency are defined as follows:

$$DPR = (Ve/Vi) * 100\%,$$

$$Eo = (Ve/Va) * 100\%$$

where

DPR = Delivery Performance Ratio;

Ve = Volume effectively delivered;

Vi = Volume intended to be delivered;

Eo = Operation efficiency; and

Va = Volume actual delivered.

RESULTS OF SIMULATION

The results of the simulation showed that the unsteady flow phenomena had an important effect on the water delivery and operation efficiency of the system, especially in the alternative of automatic upstream control. In Fig.-4, the delivery performance ratio to individual offtakes for automatic upstream control during deficiency period is presented.

The period of unsteady flow lasted about 7 hours in automatic upstream control. The time interval between two flows delivery adjustment to secondary offtake (from 50 to 100% and vice versa) was every 5 or 6 days. Within 6 days the effect of unsteady flow would be decreased appreciably, but it was not ignorable

Delivery performance ratio to individual offtake for both flows control systems during steady state condition, and sufficiency period are presented in Fig. 5 & Fig. 6. Water supplied was more than targeted, in the case of automatic upstream control, and the overall operation efficiency declined to 85.6% which is low when compared to 99.5 % overall efficiency in self-regulating downstream control system.

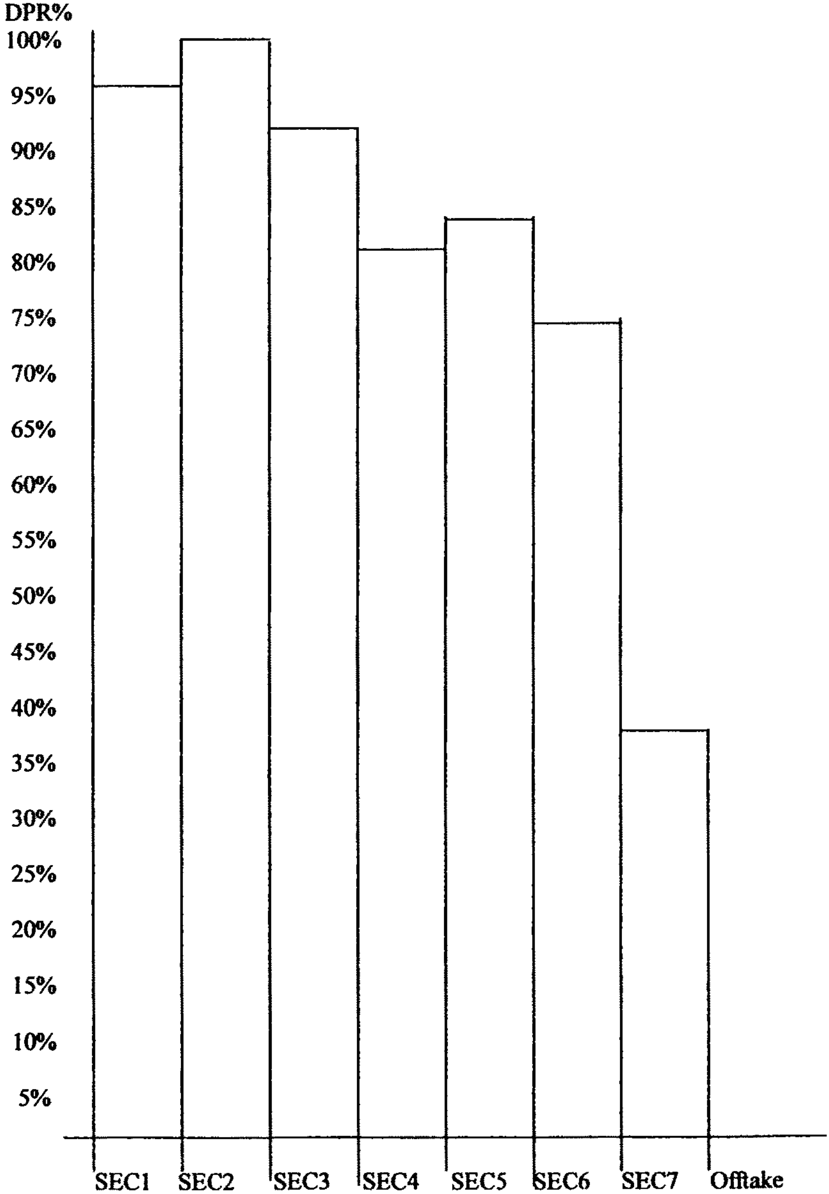

Fig. 4. DPR to Offtakes in Automatic Upstream Control During Deficiency Period

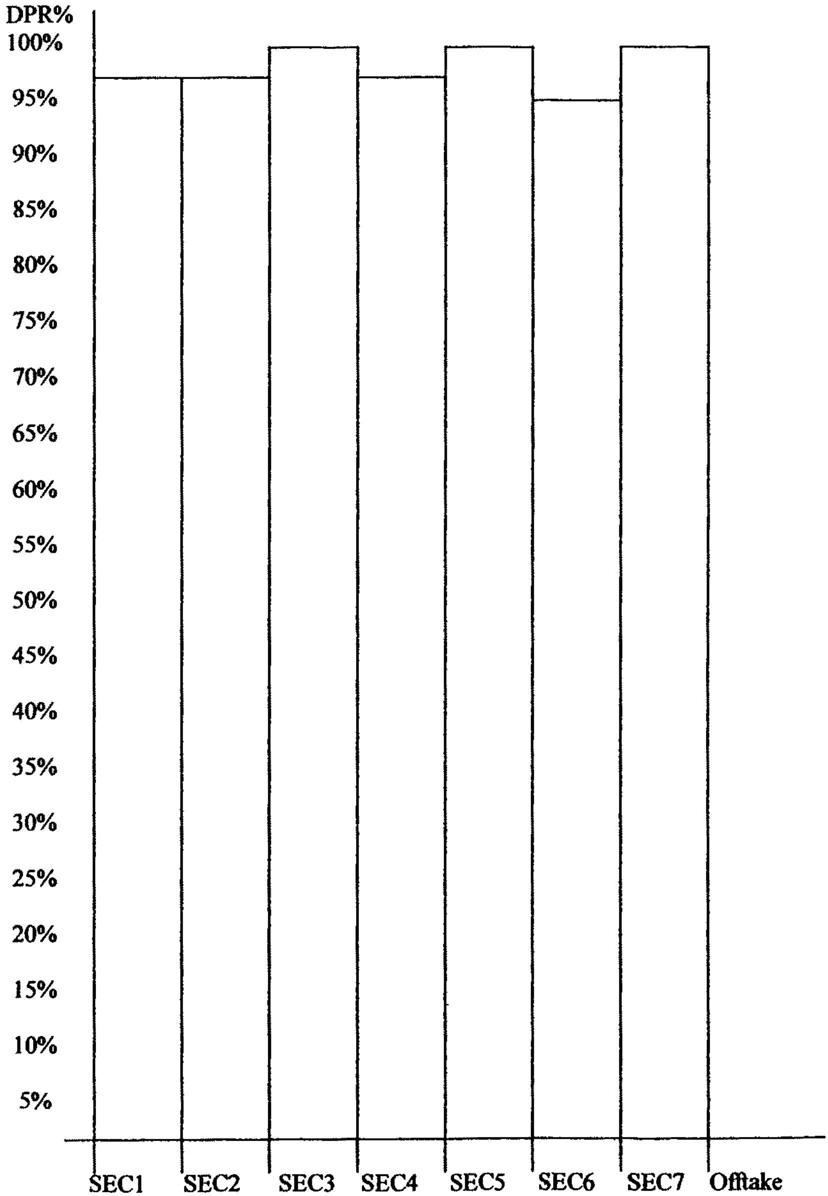

Fig. 5. DPR to Offtakes in Self-regulating Downstream Control During Sufficiency Period

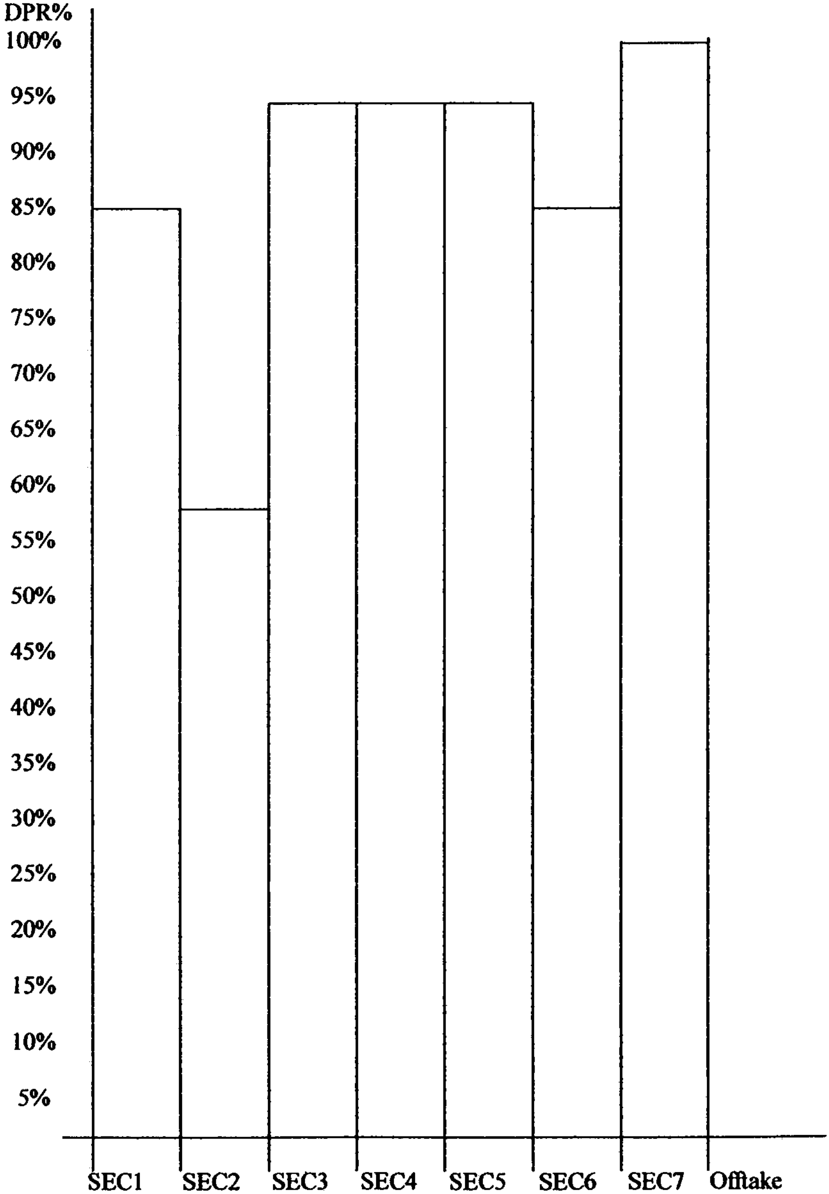

Fig. 6. DPR to Offtakes in Automatic Upstream Control During Suficiency Period

Target delivery discharge to different secondary offtakes during maximum (MAX. REQ.) and minimum (MIN. REQ.) requirement were collected in Table-1.

Table-1 Intended Discharges to Secondary Offtakes in m^3/sec

OFFTAKES	MIN. REQ. STATE 1 & 3	MAX. REQ. STATE 2 & 4
SEC1	0.26	0.52
SEC2	0.20	0.40
SEC3	0.78	1.55
SEC4	0.22	0.22
SEC5	0.40	0.80
SEC6	0.17	0.33
SEC7	1.95	3.90
TOTAL	3.98	7.94

Also, an ideal situation for taking full advantage of different sources of water during deficiency and sufficient river runoff periods is presented in Table-2.

In this table states 1 and 2 relate to the water delivery schedule to secondary offtakes during sufficient river runoff, but states 3 and 4 are occurred during low river runoff.

Table-2 Flow From Different Sources of Water in m^3/sec

SOURCE OF IRRIGATION WATER	DEFICIENCY PERIOD		SUFFICIENCY PERIOD	
	STATE 3	STATE 4	STATE 1	STATE 2
DIVERSION DAM DM1	1.26	0.60	1.57	3.12
DIVERSION DAM DM2	1.41	0.00	1.91	3.91
STORAGE DAM	1.32	7.35	0.46	0.92
TOTAL	3.99	7.95	3.99	7.95

Simulation results of SR model for two different alternatives of automatic upstream and self-regulating downstream flow control systems during deficiency and sufficiency period are discussed in the following paragraphs respectively:

Automatic upstream control during deficiency periodupstream control during deficiency period" \l 1

During minimum flow from the storage dam, a discharge of 1.32 m^3/sec was considered to be delivered to the headwork of SR primary canal. Also, two inflows with the amount of 1.26 and 1.41 m^3/sec were considered to be delivered to the primary canal at the specified locations. To begin with, it was assumed that the need of secondary offtakes was at 50% of maximum flow delivery, so the relevant module were considered half open. After reaching steady state, the two inflows were changed to 0.60 and 0.00 m^3/sec respectively. Also, the offtakes were fully (100% or maximum flow delivery to secondary offtakes) opened. In order to study the downstream demand, it was investigated as to how much and at what time water from the storage dam should be released. It was found out that for satisfying the downstream demand, it was necessary to release 7.35 m^3/sec from the storage dam to the headwork of the primary canal at the time of manual operation on offtake. It is pertinent to mention that in reality the river runoff does not change all of a sudden, but for making simulation more interesting at time of manual operation on offtake, river runoff was also changed. These actions are better observed in the model function definition in Table-3 and Table-4.

Table-3 Inflow From Diversion Dams (DM1 & DM2) Into SR Primary Canal and Water Release from the Storage Dam for the Headwork (QIN) of the Canal

TIME	QIN.	DM1	DM2
00:00:00:00	1.32	1.26	1.26
01:12:45:00	=	=	=
01:13:00:00	7.35	0.60	0.60
06:00:00:00	=	=	=

Table-4 Manual Operation on Secondary Offtake

TIME	EFFECTIVE WIDTH OF SECONDARY OFFTAKES						
	SEC1	SEC2	SEC3	SEC4	SEC5	SEC6	SEC7
00:00:00:00	0.50	1.00	1.50	1.10	0.80	0.85	3.80
01:12:45:00	=	=	=	=	=	=	=
01:13:00:00	1.00	2.00	3.00	2.20	1.60	1.65	7.80
06:00:00:00	=	=	=	=	=	=	=

In the first trial, although the operation efficiencies during minimum flow was 100% (Table-5), it was realised that some of the secondary offtakes were not fully satisfied, because, the DPR parameter for offtakes no. 1, 2, 4, and 6 were 83, 58, 72, and 75% respectively. During maximum flow, operation efficiency for the same offtakes was slightly lower, but delivery performance ratios (Table-6) were much better.

Table-5 First Trial in AutomaticUpstream Control During Minimum Flow (Steady State Condition) and Deficiency Period

Point	Operation Performance Parameters							
	DPR %	Eo %	Qtarg	Qmean	Qmax	Qmin	Tbegin	Tend
SEC1	83	100	0.26	0.21	0.21	0.21	01:00	02:00
SEC2	58	100	0.20	0.12	0.12	0.12	01:00	02:00
SEC3	91	100	0.78	0.71	0.71	0.71	01:00	02:00
SEC4	72	100	0.22	0.16	0.16	0.16	01:00	02:00
SEC5	95	100	0.40	0.38	0.38	0.38	01:00	02:00
SEC6	75	100	0.17	0.13	0.13	0.13	01:00	02:00
SEC7	100	100	1.95	1.95	1.95	1.95	01:00	02:00

$DPR_{overall}$ =91.90% $Eo_{overall}$ =91.90%

Table-6 First Trial, During Maximum (Steady State) Flow and Deficiency Period in Automatic Upstream Control System

Point	Operation Performance Parameters							
	DPR %	Eo%	Qtarg	Qmean	Qmax	Qmin	Tbegin	Tend
SEC1	98	100	0.52	0.51	0.51	0.51	01:00	02:00
SEC2	100	94	0.40	0.42	0.42	0.42	01:00	02:00
SEC3	98	100	1.55	1.52	1.52	1.52	01:00	02:00
SEC4	100	96	0.44	0.46	0.46	0.46	01:00	02:00
SEC5	100	99	0.80	0.81	0.81	0.81	01:00	02:00
SEC6	100	96	0.33	0.34	0.34	0.34	01:00	02:00
SEC7	98	100	3.90	3.83	3.83	3.83	01:00	02:00

$DPR_{overall}$ =98.50% $Eo_{overall}$ =98.50%

Therefore, there is some room for improvement in management during minimum flow. Releasing more water from storage dam is an option for increasing delivery performance ratio for offtakes that do not receive sufficient water. But this option is too costly, and management is always looking for a cheap solution.

DISCUSSION AND CONCLUSIONS

Since a Duckbill check structure was used as water level regulator in upstream control, during steady state and sufficiency periods relatively more flow (75% more) should be released from storage dam as compared with its variant alternative of self-regulating downstream control system. Most of the flow is lost at the end of SR canal to the drain, and could not be used by the secondary offtakes. It is felt that management in automatic upstream control is rather difficult, whereas for the self-regulating downstream control system management is relatively easy. In automatic upstream control during 50% delivery to secondary offtakes and steady condition of deficiency period, the offtakes were not satisfied (delivery performance ratio was low) accordingly. Therefore, step by step, more shutters of offtakes were considered to be opened, and the simulation was carried out in order to find out the best opening width (with maximum overall efficiency) for the secondary offtakes. Without a hydrodynamic model, if not impossible, it would be very difficult to establish the best opening width of the secondary offtakes during both periods of deficiency or sufficiency and steady state condition. In self-regulating downstream control system, instead of double baffle distributor for secondary offtake, single baffle could be used very effectively while it does not function properly in automatic upstream control. However, the high cost of top level embankments for the steep SR canal makes it very difficult to accept this alternative. Particularly if one pays attention to use of three relatively long syphons (SR canal is crossing one river, and two water courses), use of self-regulating downstream control could not be justified without economic analysis which is out of the scope of this report. An alternative of self-regulating system which would not need horizontal embankments is BIVAL or ELFLOW system. Since both of these systems are dependent on external power supply, they are not recommended for Shafarud Irrigation Project. Finally, the idea of taking into account the operational performance of new irrigation system at the time of design is becoming increasingly important every day, especially when it is realized that many old irrigation schemes do not function properly. One of the main reason is that water distribution and unsteady flow condition were hardly considered at the time of their design. After observing the results of simulation of unsteady and steady flow conditions in the primary canal of the Shafarud Irrigation Project, **automatic upstream control** with the following modifications and suggestions for upgrading the performance behavior of the system is considered to be better design option.

- Using an Amil gate for the water level regulator instead of Duckbill check structure;

- Change water delivery schedule to secondary offtakes and extend the time interval between two gate adjustments to at least one month in order to reduce the operational losses which are due to unsteady flow phenomena;

- Use hydrodynamic flow model for finding the best position for offtake opening during minimum flow delivery and steady state conditions.

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IRRIGATION WATER.MANAGEMENT.AND PRIVATIZATION OF IRRIGATION DELIVERY SYSTEMS — SRI LANKA

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ABSTRACT

Sri Lanka has a long history of hydraulic civilization for the last 2600 years of recorded history. Present day farmers use surface water and effective rainfall for their cultivation in the wet zone of Sri Lanka. But in the dry zone areas available surface water is not sufficient and hence water is collected into reservoirs. Traditions and conventions govern water use. A few reservoirs generate hydro-power in addition to irrigation and water supply. Construction of reservoirs is a state duty and land was allocated to farmers under the Land Development Ordinance. The Irrigation Department and the Mahaweli Engineering and Construction Agency maintained the irrigation systems from the commencement and hence operation and maintenance cost was paid by the state. The farmers were not taxed but cultivation was for rice under accepted principles. During the last 40 years, measures were taken to improve the crop yield by substitution of hybrid varieties and improved irrigation water management to optimize net income to the farmer. However many projects are not yielding sufficient income to the farmer and state liability is continuing. Formation of farmer organizations and raise the standard to stable farmer companies were tried but handing over of over all responsibility is not decided yet. The paper discusses the benefits and losses of the proposed system.

INTRODUCTION

Sri Lanka had 65519 sq km land area with 18 million population in 1998. (The National Atlas of Sri Lanka) The country is primarily agricultural with 70% of the population engaged in agriculture. The staple food is rice and people consume live proteins and vegetables along with rice and bread. The country is divided into a wet zone and a dry zone by a 2000 mm isohyet. The dry zone in the north-east part of the country has 2/3 of the land area with 1/3 of the population. This area was developed for the last 2600 years and supported the nation as a hydraulic civilization. The 12th century had the peak of development in water resources, which produced rice and exported to Burma. The rainfall was collected in

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reservoirs and used for irrigation. Diversion schemes brought water to reservoirs from rivers. Hence the land was prepared and seasonally cultivated by proper methods. Embankment, spillways and sluices were of high quality to match modem day levels. In recent years the dry zone was under heavy jungle which covered the traces of old irrigation structures. Gradually these jungle areas are converted into colonies and irrigation was continued in all streams from 1830 to date.

WATER UTILITY

Traditional methods were adopted to cultivate local rice varieties in various parts of the country. Due to low population and abundant resources, those projects provided sufficient food for the nation. Many projects were renovated and the same command area was developed for modem days. Indika rice variety was sown in lowlands while chena lands were used for grains and vegetables. The new introduction of japonica rice derived high yields and the Department of Irrigation, Department of Agriculture, Department of Agrarian Services and Mahaweli Development Board were responsible for accelerated development of water resources. The jungle is now reduced to 23% of the land area. Flood control measures were done in the wet zone to divert water and eliminate flooding in the basins. Hence lands were protected from flooding, but the wet zone drained soils were of poor quality to get high yields. Dry zone undrained soils retained high quality and yield is high.

WATER MANAGEMENT

The land and water resources are limited in irrigation projects. Due to this limitation it is planned to optimize the income of the farmer with in projects. The optimization procedure took a long period to modify the project. Hydrology of the project area is analyzed. Hence water requirement for rice crop is gauged and computed by records. The irrigation duty was noted to indicate the necessary head of water for rice in one season. This is in addition to the effective rainfall on the farmland. Conveyance loss and evaporation loss is nearly 50% of the available surface water in the reservoir.

METHODS OF WATER MANAGEMENT

All the villages in the dry zone are depending on storage water. When a reservoir breaches, people migrate to another village. Water is the life supporting material which is scarce and by tradition, all villagers possess knowledge to use water carefully. The tank storage is carefully utilized after receiving maximum capacity at the spill level elevated by temporary gunny bagging for last stage of spilling. Then this water is retained until drought is reached. Water issues are carefully done to economize water and all the leaks are controlled by keen actions. The drainage water flows into the next tank in the cascade and hence it is not wasted The dead storage is used by all people and animals. Water quality is kept clean under natural conditions. Traditional water management in village tanks were not seen in major tanks. Farmers are selected by distinct areas and live separately. Farmers are grouped and fight for more water without any consideration for managing. Upstream farmers are accustomed to getting more water from the beginning of water releases. The tail end lands were developed from a later date and naturally caused reaction from upstream farmers.

WATER SHORTAGE

This is very often recorded in many projects due to wastage. Measures were taken to identify the lands, which need more water due to the gravel content of soil. These lands are abandoned after identifying. Again low yielding lands due to iron toxicity and rocky nature are also eliminated and converted into vegetables or chena lands. Deep percolation can be reduced by such measures. Lining reduces percolation water loss of canals. Excessive water use is allowed if available but otherwise effective rainfall is allowed to reach the target by cutting down canal supply well before the rain is dropped. Land preparation with early rains accelerated the crop growth passage and hence high yield with low water use is reached by careful management practices.

WATER MANAGENMNT TECHNIQUES

Farmers are encouraged to use water saving practices by rotational issues of water. Branch canals are opened in rotation and measures are taken to make decisions under unanimous agreement of farmers. The drainage water, which is usually drained out of the farmland, is suitably used for the next farm tract in the new designs. More resident time and longer travel reduced the soil loss from the farm. Water metering devices are fixed to gauge the flow in canals. Depths of water gauges are calibrated on the walls of structures, which will assist operators in the control of gates. The yield per unit of water was improved by training the farmers in many projects.

WATER MANAGEMENT SECRETARIAT

The Mahaweli system is operated by a preplanned system with expected targets and coupled with hydropower generation. Water management staff was trained to take corrective measures in continuous operation. The serious drought situation occurred in 1992, was handled by the staff with low damage, who distributed water carefully. Another drought situation occurred in 1996 and rainfed cultivation failed. Reduction in cropping intensity according to the availability of water was decided to save part of the crop. (Seneviratne, 1996)

POLICY CHANGES IN IRRIGATION

Water management was further strengthened for optimization of net income to the farmer. Hence it is planned to implement all possible measures for any locality with the help of all state institutions and farmers. Due to low quality of soils in many projects, it is difficult to improve further without a sizeable investment on fertilizer and weed control. The economic policy decisions and regular import of food materials also decline the income levels of farmers. Many projects were assisted by foreign monetary sources at the inception. Joint planning has taken place in last decade for sustainability of the irrigation projects.

Agriculturists have taken climatic factors also into account in deciding cropping intensity and cropping calendar. Serious drought situations and El Nino effects predicted difficult planning for rice vegetation. Rain-fed irrigation in both the dry zone and the wet zone was partly abandoned due to low income against rising labor cost.

PRIVATIZATION OF IRRIGATION PROJECTS

Aim

The maintenance cost presently undertaken by government is eliminated if the systems are handed over to private organizations. If the system needs some state assistance, that money can be directly . given to the private parties without any control from the state. The loan facility is exercised through banks on recoverable basis. Hence the government is no longer bearing a liability to finance the operation and maintenance component of irrigation schemes.

Introduction

The idea of privatization of irrigation projects was developed after 1950 and it was originated in the Philippines. The present system of operation and maintenance in Sri Lanka has a long history. In 1900, the Irrigation Department was established to prevent roads getting under water. The railway line in Vavunia was shifted over and over but flooding was not stopped. Hence separate sets of engineers were needed to handle water problems. Hence the Public Works Department was separated and the Irrigation Department was formed. New engineers were recruited from the United Kingdom. The prime aim was not only to do flood control, but for development of water resources for supplying food to the growing population in the island. Indian laborers brought for tea cultivation in upland areas needed more food supply.

Hence the population in 1830 was doubled in 1930. Abandoned water resources were restored to feed the new nation. The railway was extended and the country became an export-oriented colony in the British Empire. The closed nationality of Ceylon Kandyan Kingdom known as "Sinhale" was opened up by the tea industry. Chena lands were converted into tea estates. Villagers were forced to work in tea lands but failing that Indians were brought and housed in line rooms from 1842 onwards.

Sinhalese created chaos over the development. Excess population was moved for farming in new colonies. Jungle was cut and tanks were restored, one by one which created a professional support for selected farmers. The land was originally remained as abandoned and water was freely drained to the sea. New roads were developed to keep relations between displaced citizens from home to colony. Coastliners traveled to remote villages in search of jobs. Unemployment was growing in the thickly populated coastal sector. Any investor from the United Kingdom could obtain 100 ha and develop his own estate. He was assisted by state and trade companies' loans. Roads, bridges culverts were erected for the transport. Machinery was imported for tea making and rubber rolling. But agriculture needed only the reservoir and the sluice. Farmers did their own development traditionally and hence the restored tanks were entirely given to farmers.

The inter war period was seen as an era of migration. Many Ceylonese went to Singapore and Europe. Malaria killed many people while cholera, leprosy, small pox and infant mortality prevailed all the time. The Agrarian Services Department (ASD) strengthened traditional village tank. The Irrigation Department (ID) controlled major tanks. Minor tanks with less than 400 ha command area were handed over to ASD after construction, but ID did any rehabilitation work. Major tanks were constructed at the same location of the ancient tank. Diversion schemes were developed using old structures and canals. Necessary structures were designed and constructed using engineering skills copied from India.

In the post world war period, independence was granted and universities were producing local engineers to serve in the Empire related Commonwealth. Major dams were constructed to generate hydropower and irrigation. Gal Oya, Walawe and Rajangane were built using skills of local engineers under local funds. Laxapane hydropower project was commissioned in 1950. Foreign aid was utilized in completing Mahaweli Development Project. Hydro-power capacity was improved to 1100 MW. Nearly 750 000 ha of land were under irrigation for rice crop.

Duty of the Control Agency

The Mahaweli Engineering and Construction Agency, Irrigation Department and Agrarian Services Department are performing operation and maintenance works of irrigation projects. This major irrigation project in Sri Lanka needs a higher rate to maintain the irrigation system for operation. Rehabilitation work undertaken by foreign funded projects provided the necessary modifications to improve working conditions of head works and irrigation system. Operation and maintenance staff and machinery were financed by the state. Water distribution from the main sluice to distributor canal was operated by the state. Field canals are maintained by farmers.

Farmer participation

Farmer participation was greatly discussed in the last two decades. The rainfed irrigation system was entirely handled by farmers. Land owners or tenants get together and decide the land preparation and cultivation according to the season. In Sri Lanka, the two seasons, Yala and Maha, need careful land preparation and cultivation to time the flowering phase of rice to the June - July period for Yala and the December - January period for Maha to get the good harvest from paddy cultivation. Hence delay in rains can cause upsets in the practice. A short term paddy variety is sown when the season is short with the late arrival of rains. Otherwise farming is abandoned due to drought. The government has no control over the farming. The state handles land disputes and tenant farmer issues through the Agrarian Services Department. Cleaning the drainage canals is done under maintenance votes. Agrarian Services staff is less competent in technical matters as they are not doing rehabilitation or construction.

In the major and medium irrigation projects, the protection works of structures play a leading role in the maintenance. Operation work is limited to issuing water as decided by farmers. Major and Medium irrigation works needed construction of structures and embankments for the rehabilitation. Farmers who have organized societies with financial backing undertook these contracts. Few farmers of a society undertake these works and gain individual profits. The Farmer Organization retains 10% of all money and sublets the work to individual farmers. Contribution of 10% of work by farmers is compulsory if Asian Development Bank or any other bank assists the work.

Hence rehabilitation work was successfully done using the consultation from farmers. But the farmers are not rich due to the low level of profits from paddy cultivation. Cheap rice is imported from India, which brings down the market price of rice in the local market. Rice is the staple food of all citizens and still self-sufficiency is not achieved. Droughts have caused low yields in many years. The Irrigation Department and Mahaweli Economic & Construction Agency have reached maximum irrigable area in the dry zone under the reservoirs. Presently 0.6 Mha rice fields are under them and it is proposed to reduce the burden of maintaining them any longer. Water releases are for rice cultivation only. State control is given for all irrigated crops under tanks.

Farmer Companies

The present situation is used to plan farmer companies. A Farmer Organization has no financial backing to deal with all expenditures necessary for the upkeep and maintenance of the reservoir system. Also it is in par with the state policy. Traditional farming has no deviation from the existing cropping pattern and cropping intensity of irrigated lands. More profitable ventures are necessary to increase farmer income. Other field crops have recorded more profits in few areas by growing export-oriented crops or market oriented vegetable crops. But this has a limitation in cropping intensity. No crop has a more permanent profit making ability than rice in the long run. New lands yield more income and gradually reduce income due to degradation, hence creating unemployment among farmers in a few years. Dependability on agriculture is very low when compared with industrial employment. The well-maintained reservoirs may be in danger if the decisions were not firm to sustain economic and social needs.

Privatization of Irrigation Systems

Privatization is defined as handing over the system to individual parties who are stakeholders of the system. They are not depending on the government funds but are earning profits for their own sustenance. They can decide on water use and land use. Cropping intensity, cropping calendar, cropping pattern are all decided by the directors of the company. When the system is given away by the state it is not a government property. Companies can undertake rehabilitation work, if it is fruitful to them. Expert help in the Irrigation Department can be obtained on contract. litigation staff can retain irrigation camps and premises but it is not getting funds to maintain camps. Hence the camps are fully vacated by the Irrigation Department or rented out for another department. Spare parts and stores maintained by the department will not be useful. Hence the stores material are to be shifted to a central area where the services are continued for all areas. The officers serving in the department may not increase due to curtailing of funds. Mahaweli Economic & Construction Agency reduced staff after paying compensation to 50% using donor funding. Mahaweli lands are to be handed over to the Irrigation Department according to earlier expectations but now it was decided to hand over to farmer companies.

CONSTRAINTS IN PRIVATIZATION

The pressure from aid groups is so high that it needs to take suitable action for privatization of irrigation systems. Some aid groups have given deadlines for the implementation. Therefore the handing over work should be done in a planned manner.

Owner Responsibility

ID and MECA realized the ownership needs of the system. The owner protects the system against all hazards and he passes the complete system to the next generation. Any damage done to the project is repaired so that the uses are not disturbed. Life span of the system is not unusually curtailed by the owner even at any cost. Hence ID and MECA always look at the rehabilitation work and request the government to provide funds. The experts in the ID and MECA always decide the needed repairs to the system and hence careful attention is given to all major components of the system. This superior maintenance care is not possible under an individual businessman whose primary interest is only to get a profit margin. The national budget is available to help any shortage in any funding requirement as the system is considered as a national asset. The new owner has no other asset to guarantee a funding source. The ownership requirement can be given on rental basis. In that case, the system is given on rent to the Farmer Company. The company receives the benefit but it has to supply operation and maintenance expenses. The benefit is to the company but it sells the product to the country, which has a national benefit. The necessary rehabilitation funds can be requested and taken on loan. But in case of default, the farmers are responsible for the settlement of the loan and their private funds are necessary to settle the loan. They are not allowed to sell the shares of the system as it is a property of the state. Then the company is not asking for heavy funds to repair the system.

Turnkey System of Handing Over

The government can entirely hand over the irrigation system to a company. In this case the farmers are stakeholders and they are the primary shareholders of the company. If the company selects new shareholders by multiplying the uses such as tourism, fishery, hydropower etc. then the net effect will be a payment of annual tax to the government for the period of operation. The present system of leasing of lands under land development ordinance has the annual tax calculated as 4% of the total value of the land. If irrigation water is issued, a water tax is scheduled but farmers do not pay this tax after political feedback. Hence the present tax is limited to land tenure only. Land development is coupled with colonization measures adopted to settle people in these colonies. The 2 ha land plot of land given in 1950 is now reduced to 1 ha per family selected from suitable people due to heavy demand and increase in population.

The 2 ha given in 1950 is either leased or fragmented to smaller pieces by grandchildren. Unemployment and education has shown a discouraging trend among farmers. Hence the privatization needs careful measure of shareholding in future. If the land units are taken as number of shares, the fragments create a problem in awarding shares. If the farmers are asked to purchase shares, water pricing is necessary to evaluate the use of water and individual input is measured by wages for labor. The present system of an individual farmer spending his money and labor for the cultivation is an easy approach for evaluation. Any deviation from this concept will be bureaucratic manipulations despite the low education of farmers.

Farmer Organization (FO) as a Company

This has a successful approach to the issue in the present situation. The major benefit of rehabilitation is given to the FO by awarding the contracts to its members. It has the employment benefit and the profit expected by doing a service to the nation. Big contracts are broken into smaller parts and the FO undertakes each part in successive order. RS. 0.9 million work is undertaken by 3 units of RS. 0.3 million at any time. The FO completes the work and undertakes other works. The FO has taken over smaller tanks below 400 ha from the state. Farmers successfully do maintenance of these tanks but they come across difficulties in case of flood damages. Diversion structures need careful repairs as that diverts water to required farms. Failure of a diversion abandons the command area beyond that structure. Hence the FO with more diversion structures needs more 0 and M funds than the ordinary system with one sluice canal. The rehabilitation work is gauged by status of essential repairs needed to the system. A well-maintained system needs less rehabilitation. But the rehabilitation work is always associated with bad maintenance work or negligence of farmers. This is a negative aspect of rehabilitation, which facilitates the bad farmer. If the farmer gives 10%, the state will give 90% to the system from the national budget. Traditional habits of this type will be eliminated if the Farmer Company feels that the system belongs to them and nobody is supporting the cost of repairs in the future. This fact can lead to the failure of the company. What will be the situation if the company bankrupts is a question to be answered.

Benefits of Farmer Companies

Farmers are eligible to form into a company. They can form necessary capital by buying or selling shares. The share capital is the basic fund, which can support the operation of cultivation. A seven-member board of directors directs the company. They can make decisions for implementation of marketing facilities. Market-oriented products can be processed. Cropping pattern is directed by it with individual capacity. Rice can be reduced against vegetables. Hence this flexibility is necessary for the agrarian laws of the country. Then farmer can irrigate various export- oriented crops with suitable processing capacity and preservative conditions. The income will be doubled and profits will be shared by shareholders. The company needs a management office and a work site as the case may be. It has additional maintenance costs, which will be a burden to the company. Cash crops need more employment from men and women. Hence it can absorb marketing, transporting, machine hiring and any undertaking in the future. The traditional farmer has a low potential for financing, but the company is a stable unit which can tolerate losses. If the company is large enough, it can undertake other commercial activities in the area. Further construction works also can be undertaken. The primary benefit is the relaxation on the part of the government. State controlled water resources development will come to an end. The annual budget for ID is RS. 1300 million for the work to be done in improvements, flood damages, new projects, operation and maintenance of existing works, design and investigation for future works, etc. It will be reduced by RS. 50 million if O&M works are handed over. But this will not show a remarked decrease unless capital projects are curtailed. As the island is now 75% developed in water resources, it will not be a problem. The solution will be a profit making industry with economical use of water. For the better taxing process, water pricing is necessary. The amount of surface water used and the amount of ground water used has to be priced for all industries. International investors also can join these companies.

Danger in Handing Over of Irrigation Systems to Farmer Companies

The present system of water resources development is a continuous process and hence it will last long to produce rice to the nation with all the set backs in operation and maintenance. If companies are given the freedom to develop, land and water resources, it will change the cropping pattern and cash crops will be cultivated. The rice production will be dropped remarkably. Eventually the rice price will go up. When a drought occurs with global effects on crop failure, Sri Lanka has to face a famine. Available surface water is not properly used in rice production in that situation.

The criticism used against utilizing 70% of water for rice production and obtaining low yield and low income, which will waste time, money and material is a fact when considering the true nature of importation of rice at a cheaper rate from India. The critics (economists) also point out that cash crops can generate more profit by low crop water requirement. Hence dry zone areas suitable for vegetables shall be developed for new vegetables, which need little water and no rainfall. Heavy rain fall is not suitable for vegetables.

Traditional cultivation shifted for cash crops can damage the land quality and soil quality. Degradation in soil quality by harmful pesticides, fertilizers and salinity can cause permanent damage to the lands in irrigation systems. This damage done by profit makers will be permanent and irretrievable. Hence gambling on the land is not recommended. Girkin cultivated lands experienced degradation as recorded in Mahaweli Project.

Pollution of lands is a definite criterion as a result of cultivation with suitable chemicals imported to the country. Natural manure is not sufficient to get a high yield and artificial fertilizer will definitely degrade the soil quality. The land fertility is generally reduced from a high level at the beginning to a low level in 10 years. This is due to reduction in NKP sources in the topsoil. Hence we expect companies to degrade the soil and abandon the command area very soon. The result will be unemployment and famine in the dry zone areas. To avoid this situation, new command areas are needed to use same source of water.

Upstream and downstream conflicts will rise as the spill water sources are limited in many projects in the future. Hence water rights are associated with pollution levels and quantity needed. A new efficient legal procedure is necessary to justify industrial disputes of farmers. Development of new lands will be a problem, as the lands given under privatization will not be changed for quite a long time. Perennial crops such as coconut, cocoa, banana may take precedence in cash crops when rice is replaced. Continuous rice production of the country will be affected. A common dispute arbitration board is necessary to look after the individual activities of Farmer Company, as narcotics cropping is a very high income earner.

CONCLUSION

State control in irrigating 600 000ha of lowlands can be handed over to farmer companies in the near future if the farmers are ready to organize farmer companies. The donor agencies must separately form finance companies and insurance companies to avoid financial collapse in farmer companies. Water pricing is needed to collect revenue from each company, as the traditional water use shall not disturb community balance and heritage. Government planning becomes more critical as the decision making is passed on to profit n-takers as against the present system of rice producers. Cancellation of expert advice from the Irrigation Department will be a national loss, which was developed in the course of a century. Future planning to develop a river basin will become a problem if water rights are already granted to a company. It is yet to understand the impact of terrorist activities on the farmers in light of privatization.

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SUSTAINABLE IRRIGATION IN MANITOBA UNDER THE HILL FARMS - A CASE STUDY

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ABSTRACT

Under the Hill Farms Ltd., located in South Central Manitoba, diversified into irrigated crop production in 1997. The farm operation includes up to 900 acres (360 ha) of irrigated potatoes and specialty crops (e.g., grass, hybrid seed, garlic), in rotation with grains and oilseeds. The total farm base involves over 3100 acres (1250 ha). The entire project overlies the Assiniboine Delta Aquifer, an extensive unconfined aquifer which provides municipal, domestic and agricultural water supplies. The project withdraws up to 525 ac-ft (650 dam^3) of water per year from the Assiniboine Delta Aquifer, the Assiniboine River and two wetlands. Potential exists to recharge the wetlands from the Assiniboine River.

The Under the Hill Farms irrigation project was the first irrigation project on the Assiniboine River or the Assiniboine Delta Aquifer to receive a Manitoba Environment Act Licence. The licencing process considered an array of environmental issues including habitat and fisheries protection, and soil and water quality maintenance. The licence conditions include monitoring of environmental impacts. Under the Hill Farms is required to monitor water consumption, wetland water levels, Assiniboine River levels, and soil and plant nitrate levels. Under the Hill Farms also cooperates with the Manitoba Crop Diversification Centre on a water quality monitoring project to aid in research into the movement of nitrates and pesticides to the groundwater.

The Environment Act Proposal and Licence documents and confirms the producer commitment to the environment through sustainable production. In addition, the licencing process has heightened the producer's awareness of environmental issues and impacts. Ongoing monitoring will help Under the Hill Farms to refine their management practices to maintain a sustainable farm operation for generations to come and provide research information for future irrigation developments.

INTRODUCTION

Under the Hill Farms Ltd. is located in South Central Manitoba (Fig. 1). The farm converted to irrigated crop production in 1997, in order to diversify from dryland cereal and oilseed crops. By 1999, Under the Hill Farms Ltd. included up to 900 acres (360 ha) of irrigated potato and specialty crops (e.g., grass and hybrid seed, garlic). The total land base for the farm includes over 3100 acres (1250 ha), all of which has access to irrigation in rotation. Under the Hill Farms also brings in feeder cattle each fall, as a means of diversifying their operation.

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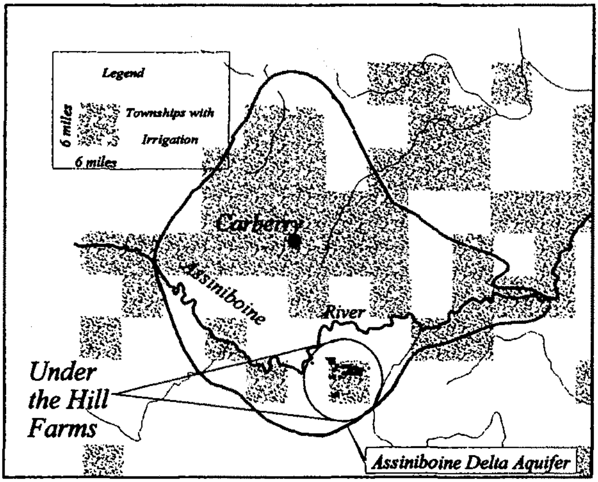

Fig. 1 - Under the Hill Farms Ltd. - Project Location

In 1997, environmental sustainability of the proposed Under the Hill Farms irrigation project was an issue for the producer as well as the public. From a public perspective, the project had several implications:

- the project overlies the Assiniboine Delta Aquifer, an extensive unconfined aquifer which supplies municipal, domestic and agricultural water;
- the project draws from the Assiniboine River, a spawning ground for the Lake Winnipeg fishery, and source of municipal water supply, waste assimilation, and public recreation;
- two surface and ground water fed wetlands are impacted; including the option to enhance recharge to the wetlands using water from the Assiniboine River;
- the public desires sustainable land management to be practiced by producers.

Sustainability is also an issue for Under the Hill Farms. Generally speaking, they have a long term interest in soil and water quality maintenance, as this is the basis for production. Moreover, Under the Hill Farms has a moral commitment to making management decisions which protect their own and their neighbours' water supplies from contamination. Lastly, any pollution of ground or surface water could put their production contracts and investment at risk due to the possibility of legal action.

For the producer, irrigation allows for diversification by limiting the risk of drought related crop failure. This is critical on the Prairies relative to securing contracts for higher value crops, such as potatoes or hybrid seed production. For the project area the average water deficit for potatoes is 4.5 inches (115 mm) and the deficit at 10% risk[3] is 7 inches

[3] 10% risk refers to the water deficit for potatoes equaled or exceeded 1 in 10 years.

(180 mm) (MB Ag, 1998). This water shortage generally occurs equally between July and August, well after major spring runoff from snow melt. For 900 acres this shortage translates to an average irrigation demand of 340 ac-ft (420 dam^3), and a demand at a 10% risk[3] of 525 ac-ft (650 dam^3).

In Manitoba, the development of this volume of water requires an environmental impact assessment and granting of an Environment Act Licence before the project can proceed. PFRA, a Branch of Agriculture and Agri-Food Canada, provided environmental impact analysis of the proposed farm practices, mitigation and monitoring measures (PFRA, 1998). Manitoba Environment Act Licence #2345 (July, 1998), was the first irrigation project licence issued on the Assiniboine River or the Assiniboine Delta Aquifer.

PROJECT DESCRIPTION

Irrigated Areas and Soil Suitability

Figure 2 shows the lands that can be irrigated in the project. The soils to be irrigated are clay loams to fine sands. Table 1 shows the percentage breakdown according to irrigation suitability[4]. Limitations to these soil types for agricultural production include moisture holding capacity (sands) to imperfect drainage (clay loams).

Table 1 - Under the Hill Farms Ltd. - Soil Suitability for Irrigation

Irrigation Rating[4]	% Project	Acres	Surface Soil Textures	Limitations
Excellent	11	345	loams	
Good	52	1648	loamy sand to sand	moisture holding
Fair	22	700	sand or clay loam	moisture holding, topography, imperfect drainage
Poor	5	147	sand	not irrigated (bush)
No Soils Map[5]	10	324		unknown

Water Sources and Infrastructure

Infrastructure: Figure 2 shows the layout of the project infrastructure. Close to 17 miles (28km) of pipelines connect 4 water sources and 6 pumps. The system will support five quarter section pivots running at 650 USgpm (41 l/s) each. Two traveling guns using 450 USgpm (28 l/s) are used in rotation with the pivots. The water sources are provided in Table 2 and descriptions of each source follows with respect to water quantity and quality.

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[4] Based on Agriculture Canada, 1987, Contribution 87-83; and unpublished data from Centre for Land and Biological Resources Research, Manitoba Land Resources Unit.

[5] 1:20000 soils maps are incomplete but reconnaissance maps rate the area good.

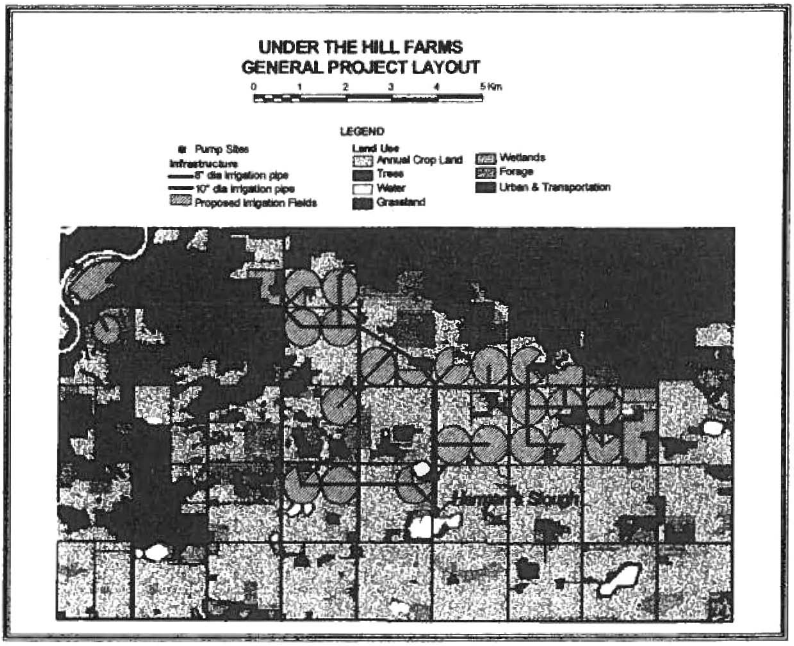

Fig. 2 - Under the Hill Farms - Irrigated Lands and Water Infrastructure

Table 2 - Under the Hill Farms Ltd. - Water Sources and Pumping Rates

Description	Volume	Water Sources	Pump Rate
Herman's Slough	200+/- ac-ft[6]	Runoff, Aquifer, pump from River	1300 USgpm
East Slough	35 ac-ft	Runoff, Aquifer, pump from River	650 USgpm
North Dugout	15 ac-ft	Assiniboine Delta Aquifer	100 USgpm
Assiniboine River Spring Summer	 200-250 ac-ft 100-275 ac-ft	Runoff, Shellmouth Dam	1300 USgpm

[6] Useable volume depends on the rate of recharge from the aquifer during July/August.

Assiniboine River: The Assiniboine River (Fig. 1) emanates in Saskatchewan to the west of the project area. Spring runoff on this River averages over 1,000,000 USgpm (63,000 l/s); while the average summer flow is in the order of 300,000 USgpm (19,000 l/s). During summer, fall and winter and droughts the River is supplemented by releases from the Shellmouth Dam (Fig. 1).

The water quality in the Assiniboine River is considered excellent for the purposes of irrigation with EC of 550 to1300 μS/cm and an SAR in the order of 1.0. Sodium (Na) ranges from 20 to150 ppm, calcium (Ca) from 40 to 600 ppm, and magnesium (Mg) from 15 to 90 ppm; with pH ranging from 7.2 to 8+ (PFRA, 1997). At times, the following parameters *slightly exceed* the Manitoba guidelines for irrigation: sulphate, iron, aluminum, manganese, nickel and the herbicide MCPA. Fecal coliform counts within the Assiniboine River can range to 200 cfu/100 ml, which is below the field crop criteria. Several other pesticides have been detected at levels below concern for irrigation; namely Dicamba and 2,4-D (KGS Group, 1999).

Assiniboine Delta Aquifer: The geologic setting for the irrigable area is the Assiniboine Delta Aquifer. The Assiniboine Delta Aquifer resulted from the formation of a large delta at the mouth of the glacial age Assiniboine River where it flowed into glacial Lake Agassiz (Fig. 1). The aquifer is a deltaic sand and silt deposit which directly overlies the clay bed of former Lake Agassiz.

The recharge to the Assiniboine Delta Aquifer is about 1 to 1.5 inches per year, with only 50%, or about 40 ac-ft (50 dam^3) per section of land, allocated for consumptive use (PFRA, 1998). Well yields in the vicinity of the project area were estimated by local well drillers to be only 100 USgpm (6 l/s) (personal comm. D. Berry), limiting the potential to provide for a larger project (e.g., 3000+ USgpm). The North Dugout was excavated into the Aquifer but the slow recharge rate limited pumping to 100 USgpm (6 l/s). For this reason the wetlands and the Assiniboine River were considered as water sources.

The water quality in the Assiniboine Delta Aquifer is generally considered excellent for the purposes of irrigation and domestic consumption. In the vicinity of the project area, water quality within the surficial sands (i.e., 20 to 70 feet) ranges from EC of 400 to 2400[7] μS/cm. Sodium (Na) ranges from 10 to 260 ppm, calcium (Ca) from 70 to110 ppm, magnesium (Mg) from 20 to 55 ppm, and pH from 7.3 to 8.

Herman's and East Slough: The Herman's and the East sloughs have surface storage amounting to 250+/- ac-ft (310 dam^3) and 35 ac-ft (43 dam^3) respectively. Herman's slough is located in an area with potential for groundwater recharge. The East slough appears to be outside the area of coarse sand deposits, having little groundwater recharge potential. Mathematical modelling predicted little groundwater recharge during the two month irrigation season. Moreover, the Herman's slough was expected to recharge by only about 50 to 75% from groundwater one year after being drawn down (PFRA, 1998).

Water monitoring on the Herman's slough (Fig. 3) confirms limited groundwater recharge during the irrigation season. No recharge or drawdown monitoring has been implemented on the East slough at this time.

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[7] The lower end of this range is more typical, with pockets of poorer quality water showing up towards the upper end of the range reported.

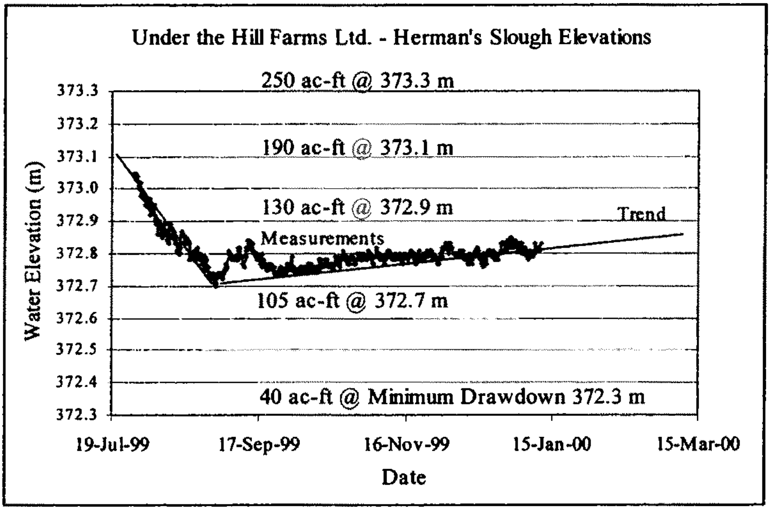

Fig. 3 - Herman's Slough - Monitoring Data (1999/2000)

Hydrologic studies indicate that adequate surface runoff for full recharge of both sloughs occurs in more than 50% of the years. Historically, the Herman's slough was dry in the drought of the 1930's (pers comm. D. Berry); while more recent infrared photos show the East slough dry during the drought of the 1980's. On this basis and given the incremental demand of the irrigation projects, the sloughs cannot be counted on as firm water supply.

Provision has been made to pump from the Assiniboine River during the spring freshet to recharge the sloughs at a rate of about 1300 USgpm (82 l/s). The Manitoba Government has not approved the recharge pumping at this point in time. Clause 14 of the Environment Act Licence indicates that:

> ... storage of water from the Assiniboine River in water storage areas over the Assiniboine Delta Aquifer (e.g., Herman's wetland) shall be considered for approval by the Director only if engineering studies show that the seepage velocity of the water from the water storage areas to the aquifer will be less than 1×10^{-7} cm/sec.

Further studies, including water level monitoring, are required to prove this is possible.

The water quality of Herman's slough (Table 3) reflects the evaporative history, the surface runoff water quality and the water quality in the upper zone of the Assiniboine Delta Aquifer. No water samples have been taken on the East slough.

Table 3 - Water Quality in the Herman's Slough

Sample Date	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	EC (μS/cm)	pH	SAR
24-02-98	128	53	216	2080	8	1.7

The water quality in Herman's slough is of poorer quality than the Assiniboine River and the Assiniboine Delta Aquifer with respect to soil and water compatibility, having an EC of 2000 μS/cm and an SAR of 1.7.[8] Maximum recommended salt concentrations on the Canadian Prairies for well drained loams to sands is 2500 to 4000 μS/cm and for well drained clay loams is 2000 μS/cm (Sask Water, 1987). For this reason the slough water supply is better suited to the coarser and better drained soils in the project area (approximately 80% of the area is coarse to medium textured). Furthermore, potato yield reductions could be as high as 12% (Sask Water, 1987) for an irrigation water EC of 2000 μS/cm and a leaching fraction of only 10%. Thus the importance of using this water on well drained soils, with a good leaching fraction.

The future recharge with water from the Assiniboine River will have small impact on the Herman's and East slough quality due to the infrequent nature of the pumping, but if anything should improve the water quality in the sloughs. Additional water quality testing on Herman's and East slough is warranted (PFRA, 1998). Additional work is warranted with respect to soil and water compatibility on individual quarters where drainage is a limitation.

BEST MANAGEMENT PRACTICES

Soil Erosion Control

Approximately 80% of the land to be irrigated is coarse to medium textured soils (sands grading to loams). Under the Hill Farms employs many Best Management Practices for soil conservation and is committed to continuing them to maintain long term soil quality and productivity.

When growing cereals and oilseeds (including annual ryegrass) the following management techniques will be employed. Many of these practices are undertaken already (*):

- leave standing stubble until spring seeding (*);
- spread manure on erodible areas (e.g., knolls) up to 300 acres/year (*);
- use air seeder to handle extra residue at seeding (*);
- use direct seeding (both into stubble and potato hills) (*);
- use noble blade for fall weed control (where necessary) (*);
- avoid soil incorporated herbicides where possible (*);
- plant and maintain shelterbelts (*);
- plant annual barriers for snow catch and erosion control;
- plant low height shelterbelts on irrigated quarters.

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[8] The water quality is likely significantly poorer (e.g., 50%) due to the ice formation on the slough at the time of the sampling.

When growing potatoes the following management techniques will be employed. Many of these practices are undertaken already (*):

- implement zero till production depending on management considerations such as affordability of chemical (e.g., Prism currently at $40/ac) and equipment (e.g., power hiller) (*);
- use non soil incorporated herbicides (*);
- use vine chopper and disc to anchor vines (*);
- perform no fall tillage on potato land (*);
- plant and maintain shelterbelts (*);
- plant fall cover crops (rye, barley) to protect soil over winter and spring (*);
- plant annual barriers for snow catch and erosion control;
- plant low height shelterbelts on irrigated quarters;
- seed corners on lighter land to cereals/forages (ie: outside pivot circle).

<u>Water Quality Protection</u>

<u>Groundwater Quality</u>: Groundwater protection involves the controlled management of inputs: water, fertilizer and biocides. Under the Hill Farms is committed to judicious use of nutrients and pesticides in order to minimize the impact on the groundwater.

The Under the Hill Farms Best Management Plan for nutrients does or may include the following techniques. Many of these practices are already undertaken (*):

- avoid fall N application (*);
- use small starter N (e.g., 50 lbs/acre in 1998) (*);
- perform soil testing (to 3' spring/fall; for fields in potatoes the following year) (*);
- perform periodic deep nitrate testing to 8 to 12 feet (every 5 to 10 years) (*);
- split N applications for potatoes (spring, at hilling and subsequent to hilling) (*);
- foliar N applications (3-4 lbs/acre/pass applied with fungicide) (*);
- perform petiole testing on potato plants (used for N scheduling) (*);
- lower the yield goal (200 cwt/acre) on lighter soils and use less N (*);
- use manure credits where applicable;
- use fertigation (in the future);
- use irrigation scheduling methods that closely match crop water requirements.

A lower yield goal is reflected in lower total N applications for the crop relative to other areas in the Province. Nitrogen applications will be split. Soil and petiole testing is used to control the amount and timing of fertilizer to minimize the potential for leaching of nutrients into the groundwater. The current plan is to use foliar application to achieve a close match to fertilizer requirements. Local researchers indicate this may not be the best method to ensure the plant receives adequate nitrogen (pers. comm. Blair Geisel). Accordingly, the Under the Hills may consider fertigation (i.e., application of fertilizer through an irrigation system).

Under the Hill Farms Ltd. does or will employ the following Best Management Practices with respect to pesticides. Some of these practices are undertaken already (*):

- use mechanical weed control (eg. during hilling) when appropriate (*);
- implement integrated pest management techniques, including blight forecasting;
- use pesticides with Immobile or Nearly Immobile ratings, and Moderate to Non Persistent properties (NDSU, 1988).

Surface Water Quality: Water quality on the Assiniboine River and the sloughs will be protected using:

- appropriate backflow prevention devices on the pipeline;
- double wall, non-syphoning fuel storage for diesel motors;
- soil erosion conservation measures (see above).

Habitat Protection - Fisheries

At the Assiniboine River pumpsite, fish successfully reproduce and survive in most years, migrating along the length of the river. For this project, impact analysis considered entrainment and impingement of migrating fish, reduced stream flows, the contribution of sediment to the stream during construction, and fuel spills.

Fish Screen: The intake to the diesel pumps on the Assiniboine River will be screened to protect fish against entrainment and impingement. Currently, a floating intake will be sized to limit the intake velocity to 0.2 ft/sec (0.06 m/s) which is adequate for walleye with a 25 mm (1 inch) length or greater and northern pike of 45 mm (1.75 inch) length or greater. The intake will have a spray bar rotating at 10 rpm to continuously clean the screen and protect fish from impingement of longer than 6 seconds. The Federal Department of Fisheries and Oceans has tentatively approved this screen.

Minimum Instream Flow: Under the Hill Farms is required by Clause 15 of their Environment Act Licence as follows:

> The Licencee shall ensure that a minimum instream flow is maintained below the diversion point at all times while water is being pumped into the Development.

This minimum flow rate, when Under the Hills will "shut-down", will be set by the Manitoba Government to protect downstream senior licences, instream biota, and recreation needs.

Pumpworks Design: The location of the intake is on a benched river flat adjacent to an outside bend of the Assiniboine River lending itself to the deep water preferred for the intake. This site requires minimal improvements resulting in little disturbance on the flood plain and within the river, with the following provisions for protection of habitat:

- stabilization of the pump pad with geo-fabrics (e.g., geo-web or geomembrane) and gravel to prevent erosion;
- provision of a double wall, non-syphoning, fuel tank (KGS Group et al., 1999) to prevent fuel contamination of the flood plain and the river;
- mobility of the pumpworks for removal during periods of high water levels.

Habitat Protection - Wetlands

A combination of surface and ground water and, potentially Assiniboine River water, will be used to maintain water levels in the sloughs. The goal is to fill the sloughs in spring and then pump from them starting in July, in order to maintain higher spring and early summer levels for the benefit of wetland birds. Late June irrigation demands could be met directly from the Assiniboine River, depending on impacts on fisheries (i.e., adequacy of the screen[9]). Adequate capacity exists to top up the sloughs from the Assiniboine River during the summer; thereby enhancing the habitat.

Drawdown levels for each slough were examined relative to the operational requirements of the irrigation project, maintenance and/or enhancement of the existing habitat and recharge characteristics (both ground and surface water). The current drawdown limits are:

East	2 ac-ft	(3.5 dam^3) volume and 7.5 acres (3 ha) surface area
Herman's	38 ac-ft	(47 dam^3) volume and 42 acres (17 ha) surface area

These limits will be modified as the operational and environmental requirements become apparent.

MONITORING AND MITIGATION

Soil and Water Quality

Several monitoring programs are in place to assess the performance of Under the Hill Farms relative to soil and water quality maintenance. Soil testing within the root zone and petiole testing determine the fertilizer requirements, while periodic deep nitrate surveys and groundwater quality monitoring provide feedback to the producer and the licencing and research agencies.

Annual Soil Sampling: Under the Hill Farms carry out soil testing 0 to 6 " (15 cm) and 6 to 24" (15 to 60 cm) for chosen fields, post harvest. The soil tests can be compared to the guidelines set out by the Manitoba Government for annual crop production. The guidelines stipulate maximum nitrate-nitrogen in the top 2 feet (60 cm) of soil as:

- 140 lb/ac for medium to heavy soils.
- 90 lb/ac for light soils.

Deep Nitrate Soil Sampling: Under the Hill Farms has used deep nitrate soil sampling to an 8 foot (240 cm) depth to provide an indication of the efficiency of their nitrogen management program. Maintaining fall soil nitrate levels at low values will minimize the risk of nitrates leaching into groundwater. Current guidelines from the Manitoba Government set maximum fall levels of nitrate-nitrogen in the soil as:

- nitrates accumulated between 0 and 4 feet (120 cm) not to exceed 150 lb/ac.
- nitrates accumulated between 4 (120 cm) and 12 feet (360 cm) not to exceed 20 lb/ac in each 1 foot (30 cm) increment.

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[9] The adequacy of the screen for pumping in June has yet to be determined.

Deep nitrate soil sampling was undertaken on two potato fields and one cereal field in January 1998 as shown in Table 4.

Table 4 - Deep Nitrate Sampling (NO_3-N; lbs/ac) Results and Government Guidelines

	Location	NE 20-7-13 W1 Potatoes, 1997			SW 26-7-13W1 Potatoes, Manured, 1997			NE 19-7-13 W1 Cereal, 1997		
Soil Sample Depth (feet)	***Manitoba Government Guidelines (maximums) (MB Ag, 1998)***	BH1	BH2	BH3	BH7	BH8	BH9	BH4	BH5	BH6
0 to 4	***150***	69	37	100	16	53	55	85	38	32
4 to 5	***20***	11	4	23	8	9	14	21	4	4
5 to 6	***20***	13	4	***34***	4	9	***33***	7	4	6
6 to 7	***20***	12	4	21	4	9	20	6	4	4
7 to 8	***20***	9	4	10	5	11	***30***	5	4	4

The results (Table 4) illustrate the following:

- results for the two potato fields are consistent with a minor number of the 4 to 8 foot (120-240 cm) samples slightly exceeding the Manitoba Government guidelines[10]. There is no apparent difference resulting from manure application[11] (BH 7, 8, 9);
- the cereal field shows lower average NO_3-N values than potatoes for the 4 to 8 foot (120 to 240 cm) samples, suggesting some downward movement of nitrates in land under potato production;
- all fields are below the guidelines for the top 4 feet and are of consistent magnitude;
- as is commonly observed, there is substantial NO_3-N level variability for the three holes in a single field leading to unanswered questions of extent and severity of soil nitrate accumulation at the field scale;
- BH3 [12] in the NE 20 shows the highest total (approximately 190 lb/ac in the top 8 feet (240 cm)) of all the sample locations but is still lower than the Government guidelines (230 lb/ac in the top 8 feet (240 cm));

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10 Both potato fields suffered serious hail damage in August 1997 or the soil nitrate values shown would likely be lower.

11 Manure applied non-uniformly on this quarter section.

12 BH3 located along a fence line and not considered to be located "in field".

Deep nitrate soil sampling is often a useful snapshot of a producer's nitrogen management program, indicating if nitrogen is being applied in excess of crop requirements. Based on the testing conducted to date in comparison to the Manitoba Government guidelines, Under the Hill Farms is doing a reasonable job of nitrogen management. Additional groundwater sampling is still warranted since the ability of deep nitrate soil sampling to pick up nitrate leaching in coarser textured soils is limited by the rapid downward movement of water and nitrates.

Water Quality Monitoring Program: The Manitoba Crop Diversification Centre (MCDC) is an industry led Centre for applied research located in Carberry (Fig. 1). MCDC has been monitoring groundwater quality since 1994 using a network of fourteen wells on the Assiniboine Delta Aquifer. To date, detection of pesticide residues were all below the Maximum Allowable Concentration (MAC) established in the Canadian Drinking Water Quality Guidelines (PFRA, 1998). Most of the monitoring wells show stable levels of NO_3-N with only three wells having levels slightly above the Canadian Drinking Water Quality Guidelines (ie. 10 ppm). For all three wells the baseline NO_3-N levels were high prior to irrigation (e.g., 11 to 12 ppm). Of particular interest here, MCDC installed a monitoring well (MW-F*) in May of 1996 in Section 20-7-13 W1.

Results of the monitoring (Fig. 4) show background (1996) levels of about 12 ppm $N0_3$-N, prior to irrigated potato production, and stable levels to the spring of 1997. During the summer of 1997, $N0_3$-N levels rose to a peak of 38 ppm (MW-F) prior to dropping back to 14 ppm in March, 1998; thereafter rising to about 20 ppm. The samples are generally from the surface (i.e top 5 feet) of the aquifer. MW-F was sampled for a wide range of pesticide residues in the fall of 1996 and none were detected.

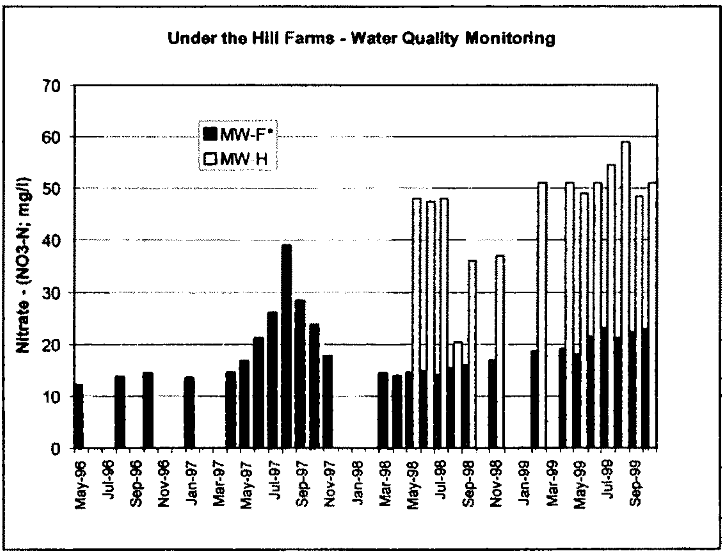

Fig. 4 - MCDC Water Quality Monitoring

Data from Oakes Test Area in North Dakota suggests that NO_3-N is typically stratified with highest readings on the surface of the aquifer and lower with depth (Knighton, 1997). Accordingly, the 1998 MCDC program included the installation of two more monitoring wells at increasing depths in order to track vertical distribution of nitrates at that site. The results from these wells show that nitrates decrease with depth to close to 0 ppm at about 12 feet (3.5 m) below the water table; consistent with the North Dakota data. A second well MW-H was installed in Section 19-7-13 W; results from this well show even higher nitrate levels in the top 5 feet (1.5 m) of the aquifer than in MW-F*.

MCDC also monitored several domestic wells in the Under the Hills Project area. One well has a recorded maximum level of 17 ppm NO_3-N (PFRA, 1998). It is difficult to tell the source and significance of the NO_3-N levels observed in this well due to the lack of historic data. The other wells in the vicinity of MW-F and MW-H that were monitored were well below the 10 ppm Canadian Drinking Water Quality Guideline (<1 ppm).

The results of the water quality program to date suggest relationships to land management practices should be investigated further. MCDC is also examining the fate of nitrate in unconfined near surface aquifers. On the Under the Hill Farms, one possibility could be that there was an initial flush of nitrate associated with change in crop rotation to potatoes and the associated increase in tillage and microbial activity. Subject to further monitoring and investigations, Under the Hill Farms may consider additional BMPs such as fertigation, planting of deep rooted perennial crops in rotation (e.g., alfalfa), and more intensive irrigation scheduling methods; if required and if economically viable.

Irrigation Water Quality: PFRA (1998) recommended the producer sample the sloughs' water quality yearly. This has not occurred. Irrigation water quality monitoring on the Assiniboine River is covered by a Government monitoring program that is in place upstream of the project. However, PFRA (1998) recommended that the producer should inform himself as to the Government mechanisms for responding to a major spill on the Assiniboine River, in order to avoid pumping any polluted water. Pumping from the Assiniboine River to the wetlands might require additional water quality monitoring at the River.

Wildlife Habitat

Monitoring of the Wildlife Habitat included a baseline survey of the vegetation type at Herman's and East sloughs, undertaken in the late fall, 1997. The survey only identified the common and indicator species. Endangered and other notable vegetation were not noted as being present or absent due to the time of year. Follow-up surveys are required to judge impact of the irrigation project and recommend further changes to management (e.g., modified drawdown and fill levels).

Herman's Slough: The vegetation surrounding the Herman's slough is host to numerous wildlife species including mammals, birds and waterfowl; most notably a bald eagle was spotted. Vegetation zones include grassland, both grazed and non-grazed, mature forest, and riparian, both shrubs and perennial (Fig. 5). Over 30 species were identified, including aspen and maple forest, dogwood and willow and cattail riparian, alkali cord grass and brome grass non-grazed grassland. Observations included the significant impact of cattle pasturing on the vegetation surrounding the west half of the slough, as indicated by the presence of snowberry (PFRA, 1998).

The vegetation along the riparian zone is already accustomed to seasonal water fluctuations as shown by the distinct zones of vegetation. The major recommendation is to establish a practical water level drawdown which will preserve the habitat associated with the wetland and provide adequate water for wetland birds during the hatching through adult molt stage (PFRA, 1998). Secondly, limiting the access of cattle to the riparian zone will enhance the value for wildlife habitat from the current state. Additional measures could include planting of trees and shrubs on the north and side of the slough, which could help with snow trapping and recharge as well.

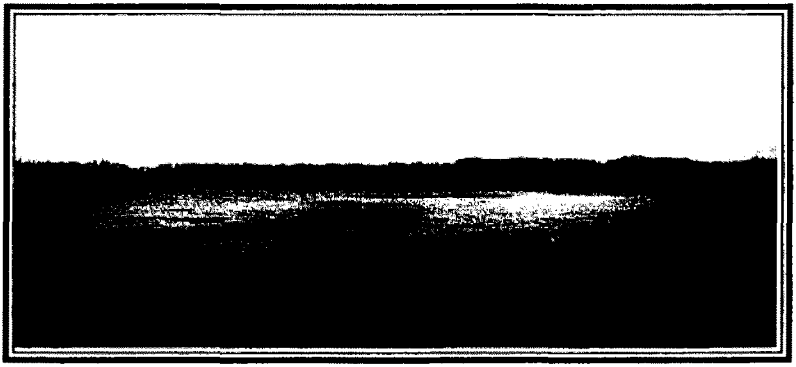

Fig. 5 - Photograph of Herman's Slough

East Slough: Vegetation is adjusted to the fact that the East slough is often dry. The site reconnaissance shows indication of a dynamic habitat (i.e., non-permanent wetland). In addition, past management practices have disturbed the habitat, including trenching, burning, mowing as evident in the greater number and diversity of perennial species.

The management of the East slough for irrigation requirements will dictate it being fully drawn down each fall. By mid-summer the reduction will be to about less than one-half of the slough area. Refilling from the Assiniboine River could be used to further limit the drawdown impacts and create a more permanent wetland similar to the Herman's Slough (albeit smaller).

Fisheries Habitat

Minimum Instream Flow Needs: Daily records of the pumping will be maintained by Under the Hill Farms and will be compared to established minimum water levels and provincial gauging stations by the Manitoba Government.

Fish Screening: The intake will be monitored in-season to ensure the screen remains unplugged, the rotating bar is operational, and screen corrosion is minimal.

CONCLUSIONS

The Environment Act Proposal and Licence documents and confirms Under the Hill Farms commitment to the environment through sustainable production practices. The licence requires Under the Hill Farms to monitor water consumption, wetland water levels, Assiniboine River levels, and soil and plant nitrate levels. In addition, they may periodically monitor deep nitrate profiles on selected fields, and are participating with MCDC on a water quality monitoring program. Ongoing monitoring in the areas of habitat protection will include periodic vegetation surveys, checking of intake screens, monitoring of Assiniboine River water levels, and observing slough drawdown limits.

Under the Hill Farms employs nutrient management techniques designated as Best Management Practices including: soil testing; lower target yields (on sandier soils); low spring starter nitrogen and split applications; foliar applications of nitrogen; and petiole testing. Fertigation, intensive irrigation scheduling, and modification of their crop rotation are the only BMPs left for them to implement. Monitoring to date indicates that pesticide movement is not an issue for this project. Deep nitrate and domestic well monitoring to date suggests nutrient management practices are generally working, but elevated $N0_3$-N results in the water quality monitoring warrant further investigation.

The licencing and monitoring process has heightened the producer's awareness of environmental issues and will help them refine their management practices to maintain a sustainable farm operation for future generations.

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INNOVATIVE STATIC SELF-CLEANING SCREEN PROTECTS FISH AND REMOVES DEBRIS AT IRRIGATION DIVERSIONS

James J. Strong[1] Robert K. Weir[2]

ABSTRACT

At the time many irrigation projects were conceived at the turn of the last century, and prior to 1930, little consideration had been given to providing screens for fish protection. The passage of the Endangered Species Act, plus recent environmental concerns for protection of fish as a natural resource having considerable economic value, however, has prompted the construction of new diversion structures to exclude both resident and migratory fish from entering irrigation canals where they would otherwise be lost. One such installation, on the Flathead Irrigation Project in Montana, included a stream diversion to accommodate a screening facility that had to be suitable for a remote location, since electricity was not available to operate a cleaning mechanism. An additional requirement for small irrigation diversions is the need to be very cost-effective and reliable with a minimum of maintenance. A screening system that meets these requirements has been developed utilizing concave screen panels arranged in a linear array. The screening system is installed along the crest of small dams or diversion structures. As the water flows over the screen, a portion passes through to the irrigation system and the remainder flows across the screen surface carrying aquatic life safely downstream. Components are fabricated from stainless steel and are designed for maintenance-free operation. The screening structure on Crow Creek, which is part of the Flathead Irrigation Project, was the outcome of negotiations between the Bureau of Indian Affairs and the Tribal Council of the Flathead Indian Tribe. Installation techniques and costs for the fish screening structure at the Flathead Irrigation Project are presented.

INTRODUCTION

The Flathead Irrigation Project is located on the Flathead Indian Reservation in western Montana within the Portland Area Jurisdiction of the Bureau of Indian

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Affairs as shown in Figure 1. The Flathead Indian Reservation was first established by the Treaty of Hellgate in 1855. At that time, the land and resources within the reservation boundary were reserved for the exclusive use of the Confederated Salish and Kootenai Tribes.

An important aspect of the reservation land ownership involved the implementation of an irrigation project in 1904, which has come to be known as the Flathead Indian Irrigation Project. In 1908, the Federal Government initiated the appropriation of funds for this project which subsequently involved the expansion of the scope of the project to include non-Indian land. Irrigated land involves the production of potatoes, grains, and hay for cattle feed.

The federal Government, through the Northwest Region of the Bureau of Indian Affairs, has the following two primary trust responsibilities as operators of the Flathead Indian Irrigation Project:

1. Efficiently and fairly delivering irrigation water to irrigators served by the project.
2. Conducting project business in a manner consistent with Federal law, regulation, and policy.

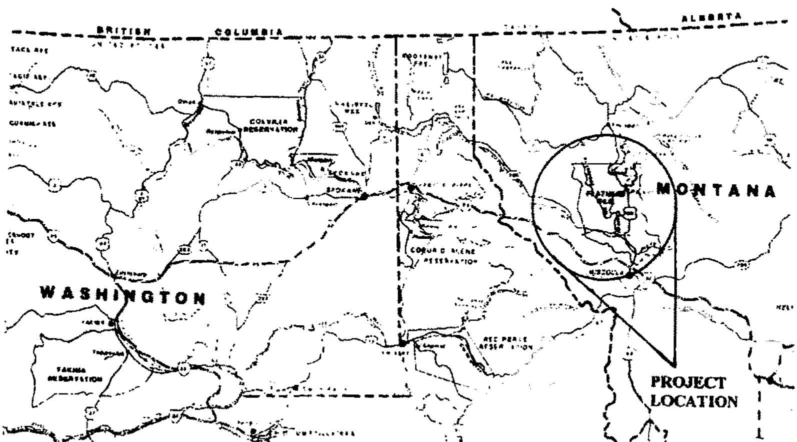


Figure 1

At the time the Flathead Indian Irrigation Project was initiated, no consideration had been given to protection of one of the most important resources of the reservation; i.e., fish, consisting primarily of bull trout (Salvelinus confluentus) and west slope cutthroat trout (Salmo clarkie) with the latter being the only native species. Seasonal demands for irrigation water from the reservation streams and reservoirs invariably led to fish losses which had adversely impacted the reservation resources. A typical fish kill when irrigation canals were shut off at the end of an irrigation season is shown in Figure 2. The fish happen to be yellow perch (Perca florescens); other species had already succumbed from the deprivation of oxygen prior to a total shut-down of the canal. In an effort to mitigate these losses the Bureau of Indian Affairs in 1987 decided to incorporate within a single structure, a fish screen, a fish ladder, and a new diversion on Crow Creek located within the reservation and southwest of Ronan, Montana. The project was done in order to protect fish and meet the trust responsibilities of the Federal Government.

Figure 2

DISCUSSION

Problems Associated With Conventional Screens

Most of the screening facilities for fish protection at diversions prior to 1983 consisted of the then state-of-the-art standard perforated plate screens. These screens are generally 14-guage punched plate with 5/32-inch holes on 7/32-inch centers. A brush mechanism, driven by cable and pulley system powered by a reversible motor, cleans the screens continuously as shown in Figure 3. In spite of the fairly inexpensive installed cost of approximately $250 per CFS (cubic foot per second) for this type of screen, there are many inherent problems. First of all, power is required to operate the brush mechanism. Since the diversion for many small irrigation sites is typically far removed from a source of power, supplying power to the diversion can be very expensive. Where icing conditions occur, the screens frequently freeze up and have to be removed during the winter to prevent damage. Pine needles and small rocks also tend to become wedged in the punched holes and clog the screen. A special clogging problem can occur with these types of screens in streams that are high in filamentous algae during summer

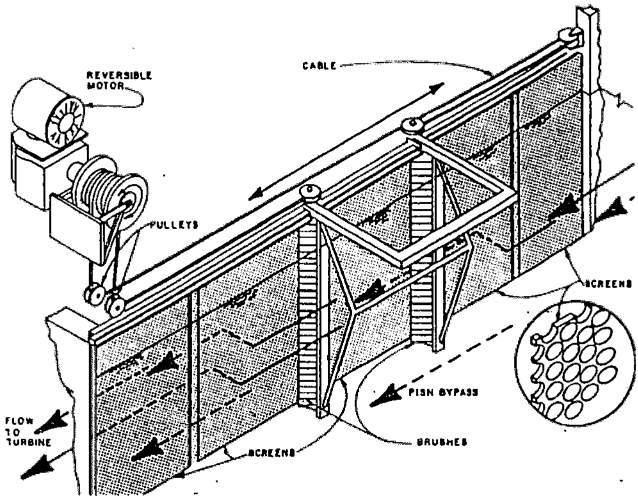


Figure 3

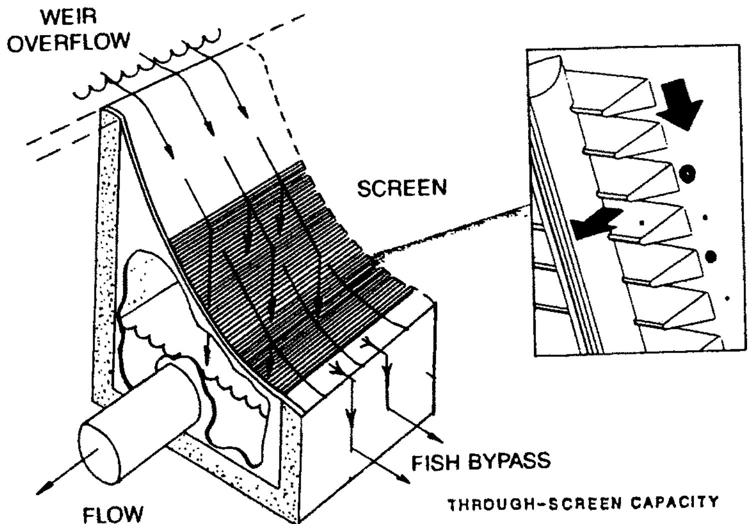
months. If a special anti-fouling coating or material is not used, repeated hand brushing may be necessary to control some types of algae growing on the screen surfaces. Finally, provision should be made to ensure that the by-pass flow parallel to the screen will remove debris carried from the screen face as well as guide fish downstream.

Practical Solution For Crow Creek

For the remote diversion site at Crow Creek, it was desirable to find a screening technique that met not only regulatory criteria, but had no moving parts or power requirements, and was simple and inexpensive to install. It was also desirable that the fish screen be self-cleaning, and require little or no maintenance. To meet all these criteria, the concept of the Coanda-type screen was selected as illustrated in Figure 4.

The Coanda-type screen originated in 1955 as a simple apparatus for wet screening slurries in the mining industry utilizing the Coanda Effect; that is, the phenomenon whereby a fluid tends to follow a solid surface. In addition, the wedge-shaped wire is tilted on the support rods during the manufacturing process.

The wire tilt produces an offset which causes a shearing action along the screen surface. A portion of water flowing over each slot is sliced or sheared off. Water flows over the weir plate and onto an acceleration plate which provides for even distribution of flow across the screen width and increase in velocity of the fluid across the horizontal slot. The screen is shaped in the form of an ogee as in a dam over-flow spillway. Flow of diverted water is through the screen slots, which are normally 1mm wide, to a water conveyance channel located beneath the screen. Because the acceleration plate increases the velocity of the water across the slots, 90% of the suspended solid particles as small as .5 mm do not pass through the



THROUGH-SCREEN CAPACITY

FLOW (CFS/FT)	DIMENSIONS A	B	C
1.0	35 3/4"	34 1/2"	4 1/2"
1.5	47"	44"	5 3/4"

Figure 4

screen. The smooth surface of the stainless steel screen provides an excellent fish conveyance to a fish by-pass. Since both the debris and fish pass over the screen surface, very little, if any, cleaning is required. The underside of the screen is reinforced with supports to handle all large debris passing over it which may include rocks and tree limbs which would otherwise incapacitate a perforated plate screen.

Generally, these Coanda-type screens are sized to handle 1 to 4 cfs per lineal foot of screen width measured at the weir crest, depending on approach conditions as well as available head loss. The cost of the screening material and supports is approximately $700 per cfs; however installation is relatively simple making them very cost-effective. The Coanda-type screen is installed by merely placing the frame assembly onto two concrete walls as shown in Figure 4. Also shown in Figure 4 are the general dimensions for flow densities of 1 and 1 ½ cfs per lineal foot of screen width measured along the weir crest.

The irrigation diversion at the Crow Creek site involved 120 cfs, and it was decided to utilize a flow rating of 1 ½ cfs per lineal foot of screen width which required a total weir length of 80 feet. Since the screen panels are normally finished in 5-foot widths, a total of 16 panels were to be placed on the structure to be erected at the site.

Crow Creek Site

The project site selected on Crow Creek for the diversion structure, fish ladder, and fish screen is shown in Figure 5. The control gates to Moiese A Canal, an irrigation diversion southwest of Ronan, Montana, are shown to the right of the center of the photograph. Particular care had to be taken so as not to disturb the tree in the center of the photograph, because markings on the tree provided indication that an encampment site was at one time nearby. During the permit process, it was decided that this tree held significant cultural importance for the Confederated Salish and Kootenai Tribes, and therefore, was not disturbed in any manner.

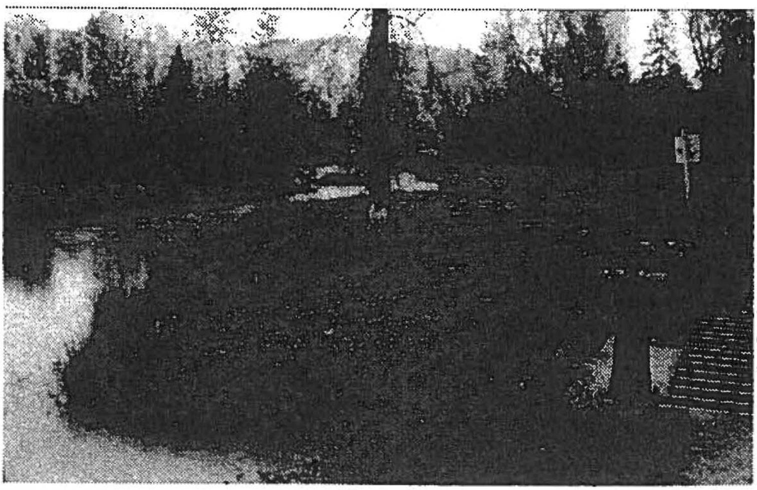


Figure 5

Construction Phase

The employees of the Flathead Indian Irrigation Project constituted the work force of this project, many of whom had never worked on a project of this size before so that this project served as on-the-job training for many of the crew. On December 31, 1987, the construction phase of this project was completed as shown in Figure 6 and the site was ready for landscaping in the spring of the following year.

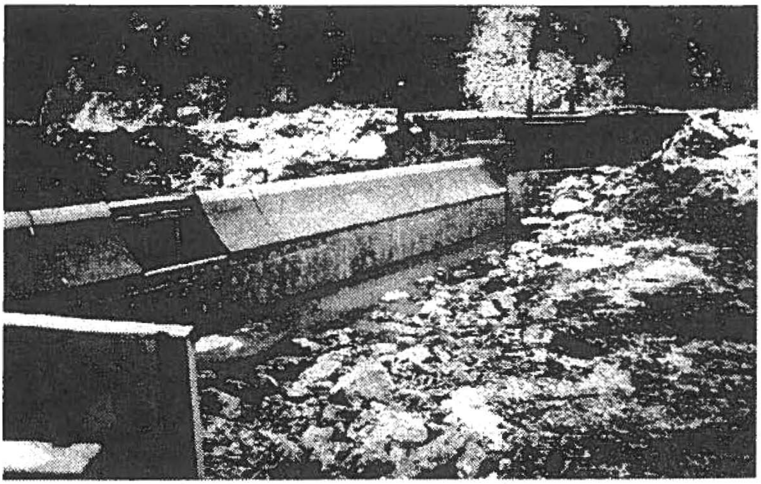


Figure 6

Cost Analysis

In accordance with the accounting records of the Bureau of Indian Affairs, the total cost of the project in 1999 dollars is broken down as follows:

Material	\$44,199
Labor	\$64,911
Static fish screen	\$72,765
Total Project Cost	\$181,375

It should be noted that this total cost reflects the irrigation diversion structure as well as for a five-step-and-pool fish ladder in addition to the static fish screen

Therefore, rather than operating at the original design of 1 ½ cfs per ft. of weir length, the screens were operating in excess of 2 cfs per ft. of weir length.

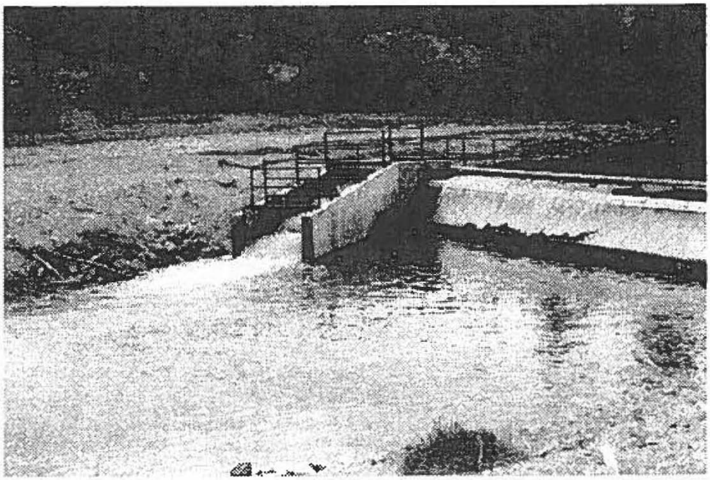


Figure 7

Soon after the static screen installation was placed in service, an algae growth was observed on the wetted surface of the screens. It was found that brushing the screens once a week removed any build-up of material on the screens.

Second Site – K Canal

As a result of the reliable operation of the Crow Creek installation, the Bureau ofl Indian Affairs decided that a second site at the Flathead Irrigation Project at K Canal should also be considered for a Coanda-type static screen. After careful hydraulic studies, it was decided that this second site on K Canal had the available head loss of 54 inches to make a static screen suitable at this location.

K Canal is a 240-cfs off-channel structure, located on the Jocko River, east of Arlee, Montana on the Flathead Indian Reservation. This second Coanda-type static screen structure was completed in 1992 and the operation is identical to Crow Creek only it is twice as long. For the 240 cfs flow, sixteen 5 ft. wide panels were utilized to handle the total flow; that is 3 cfs per lineal foot of screen width measured along the weir crest. This is virtually double the original guaranteed flow of 1 ½ cfs per lineal foot of screen width measured along the weir crest.

In light of this, the Bureau of Indian Affairs declared one-half the original total of sixteen panels at Crow Creek surplus and relocated them to K Canal site and purchased an additional quantity of eight more panels in 19192. The completed installation at K Canal is shown in Figure 8.

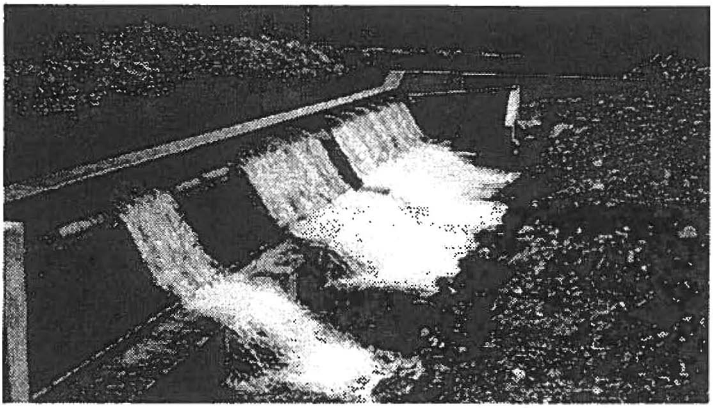


Figure 8

No decreased capacity resulted from wear on the leading edges of the tilted wires has been observed at either Crow Creek or K Canal. As the years have passed, however, increased maintenance has been required at both sites. Aquatic vegetation build-up on the screens has required high-pressure washing to clean them. Undoubtedly, the use of copper/nickel alloy for the screen material would virtually eliminate this biofouling; however, copper/nickel alloy is approximately three times the cost of Type 304 Stainless Steel and does not have comparable strength.

Summary and Conclusion

In conclusion, the irrigation diversions of Crow Creek and K Canal, incorporating the fish ladder and static screen installation, are operating as originally intended by meeting the in-stream flows as well as providing positive protection by excluding fish from entering the irrigation canals. Previous installations of the Coanda-type static screen concept had been applied to hydroelectric diversions for fish protection. The installations of Crow Creek and K Canal were the first such Coanda-type screen applications involving fish protection on irrigation diversions and show a promising concept that may be considered as an alternative to conventional fish-screening techniques. The Coanda-type screen concept, therefore, appears equally adaptable to irrigation diversions as well as to hydro diversions.

In the case of hydro diversions, the hydraulic turbine determines the flow through the screens, and reduced load means rejection of water by overflowing the screens. In the case of irrigation diversions, the irrigation demand determines the flow through the screens and should the screens not meet the irrigation demand, water overflowing the screens may be considered wasted. Therefore, it is important that the screens be sized correctly to meet the irrigation demand. There are many factors influencing the sizing of the Coanda-type screens, and in the case of the Crow Creek installation, the original design obviously was more conservative than required.

Subsequent experience with Coanda-type static screens at the irrigation diversion of East Fork Irrigation District near Hood River, Oregon has proven the capability of this type of screen to be cost effective at much lower head losses than originally conceived. For example, under the ideal approach conditions at the East Fork Irrigation District site, the differential head between the upstream level in the compartmental sand trap and the tailwater of the screen is only approximately 18 inches. Even so, the screens are still capable of handling the capacity of 90 cfs or 1 ½ cfs per foot of horizontal weir length of screen. For more information of this installation, please refer to the Proceedings of the 1999 USCID Workshop, Modernization of Irrigation Water Delivery Systems under "Protecting Fish at Irrigation Diversions", pages 637 through 644.

ACKNOWLEDGEMENTS

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MANAGING SALINITY IN NORTH-WEST INDIA: THE CONJUNCTIVE USE OPTION

Dr. N.K. Tyagi[1]

ABSTRACT

North-West India which comprises south-western Punjab, northern Haryana and north-western Rajasthan is a region with distinct agro-ecology with peculiar land and water management problems. The major part of the area lies in a semi-arid to hyper-arid zone where evaporation exceeds rainfall by a factor of 2 to 15. Alluvial deposits that underlie most of the area, contain to a great depth, a continuous body of water which occurs under phreatic conditions in a large part of the area with few semi-confined to confined aquifers occurring at varying depths. The ground water availability as well as quality decreases with increase in aridity from northeast to southwest. To correct the water demand/supply imbalance in this agriculturally productive region, extensive irrigation has been introduced through large scale diversion of surface water. In spite of surface water diversions, the water availability per unit area is low and the region is under the influence of waterlogging, salinity and alkalinity which are undermining the capacity of the region to meet its food production targets. Various long and short term options including preventive and curative measures have been examined to maintain the agricultural productivity at high levels. The long term solution lies in provision of drainage to lower the water table and leach salts, which should be disposed in a permanent sink. The existing geo-political situation and the absence of natural drainage outlets favour conjunctive use of marginal quality ground waters and drainage effluents with canal waters to tide over the water scarcity, to minimize the rise of the watertable and to reduce the disposable drainage effluents.

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In land areas afflicted with salinity under high watertable situations, conjunctive use is permissible only in conjunction with sub-surface drainage. Agro-chemical amendments together with salt tolerant cultivars promote the use of high residual sodium carbonate waters in a medium term plan. In areas with deep watertable but with high ground water salinity, cropping choices are limited and salt tolerant trees/halophytes are better options. Conjunctive use planning in ground water areas with a declining trend calls for increased emphasis on ground water recharge to sustain the existing cropping pattern. In the absence of large scale investment in the near future, the technical and socio-economic situation favours conjunctive use as medium term option for managing salinity in North-West India.

INTRODUCTION

Conjunctive use management of multi-source/multi-quality waters can be defined as the management of multiple water resources in a coordinated operation such that the total water yield of the system over a period of time exceeds the sum of water yields of the individual components of the system resulting from uncoordinated operation. The net output in the conjunctive mode is more compared to the net output when each source/quality of water is used separately. As a result of conjunctive use of surface and ground water resources, it is possible to have optimum utilization of water resources as ground water could act and function as a storage reservoir, regulation agent and conveyance medium. The separate use of surface and ground water in itself may not always constitute a conjunctive use. The conjunctive use concept recognizes:

i) the unified nature of water resources as a single natural resource

ii) advantage of the interactions between the surface and ground waters in planning the use from the two resources.

Conjunctive use is planned and practiced with the following objectives:

(1) Mitigating the effect of the shortages in canal water supplies often subject to steep variations in river flow during different periods in the year.

(2) Increasing the dependability of the existing water supplies.

(3) Alleviating the problem of high water table and salinity resulting from introduction of canal irrigation.

(4) Facilitating the use of high salinity ground water, which cannot otherwise be used without appropriate dilution.

A number of conjunctive use planning models have been developed to determine pumping rates for a sustainable potentiometric surface, allocation of water to areas under different crops and optimal hydro-salinity regimes in a basin. The economic aspects of water allocations have received greater attention and both linear (Khepar and Chaturvedi, 1982; Bhirud, 1989) and dynamic programming models (Knapp and Wichelns, 1990) have been used in such studies. Ground water simulations have also received greater attention and analytic as well as numerical approaches have found use (Helweg and Labadie, 1976; Lefkoff and Gorelick, 1990). Models that develop a quantitative understanding of economic, agronomic and hydrologic processes that occur in a saline irrigated system have been rather limited. Srinivaslu et al. (1997) developed and applied such a model to lower Ghaggar Basin.

AREA AND THE PROBLEM

North-West (N.W.) India includes parts of the states of Punjab, Haryana and Rajasthan. Agriculturally this is one of the most productive areas contributing a major part of rice, wheat, cotton, pulses and oilseeds. The climate of the area being arid to sub-humid, large-scale irrigation development has taken place in this region. The major irrigation projects that have been undertaken include Bhakra, Western Yamuna, Gang and IGNP (Fig. 1).

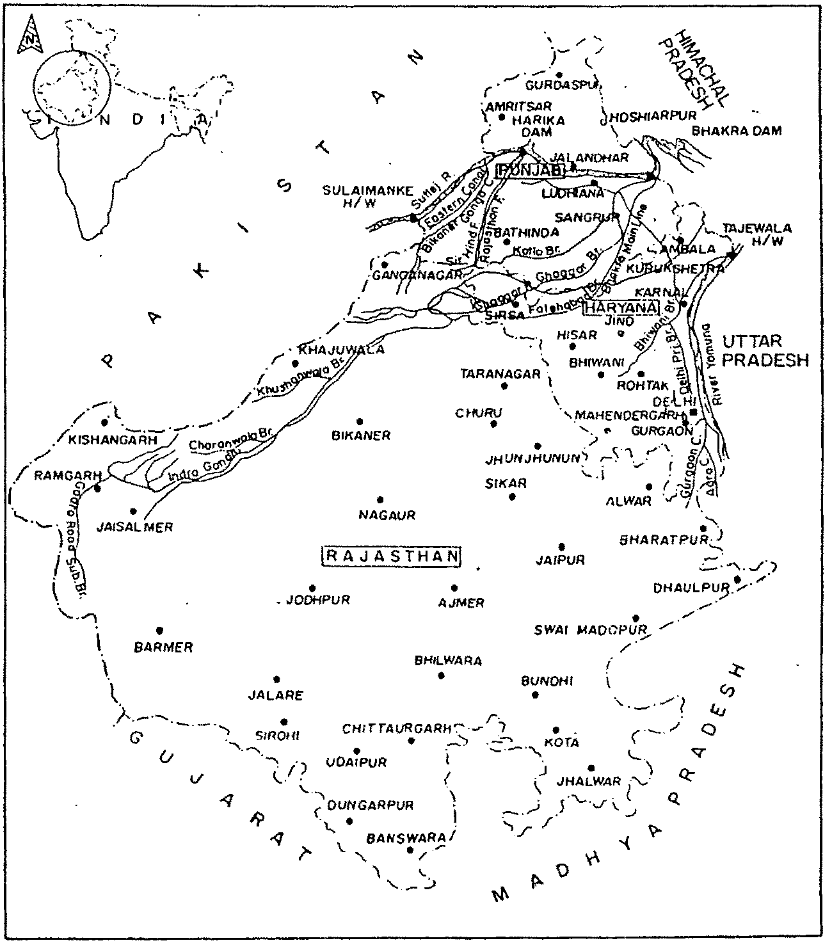


Fig. 1. Location Map and Major Canal Systems of North-West India.

A major part of N.W. India is underlain by saline ground water. At a macro scale, distribution of ground water quality in a few of the states shows that on average 59% of the ground water falls in the marginal or poor quality zones (Table 1). Specifically in the region covering Haryana and Rajasthan more than 50% of the area is underlain with poor quality waters(Fig. 2).

Table 1. Distribution of Ground Water Resources with Respect to its Quality in Some States.

State	Ground water quality (%)		
	Good	Marginal	Poor
Haryana	37	8	55
Punjab	59	22	19
Gujarat	70	20	10
Rajasthan	16	16	68

Source: Manchanda et al. (1989)

Irrigation development in this region has taken place without adequate drainage systems. In arid regions, the natural drainage, as a rule, is not very well developed. Consequently salt and water have been accumulating in various irrigation projects. An area of about 1.0 million ha has become salinized and waterlogged. It maybe mentioned that annual irrigation intensity from canal irrigation in this region is less than 100 percent and water allowance varies from 0.2 litre/sec/ha to 0.4 litre/sec/ha. The overall water supply is much below the requirements. The problems facing N.W. India are:

- Insufficient surface water supplies to irrigate the entire cultivable command area.
- Saline/sodic ground waters occurring in aquifers of low transmissivity
- Rising trend in watertable leading to salinization of productive agricultural land.
- Falling trend in watertable in fresh ground water areas leading to increased pumping costs.
- Absence of outlets for disposing of saline drainage effluents.

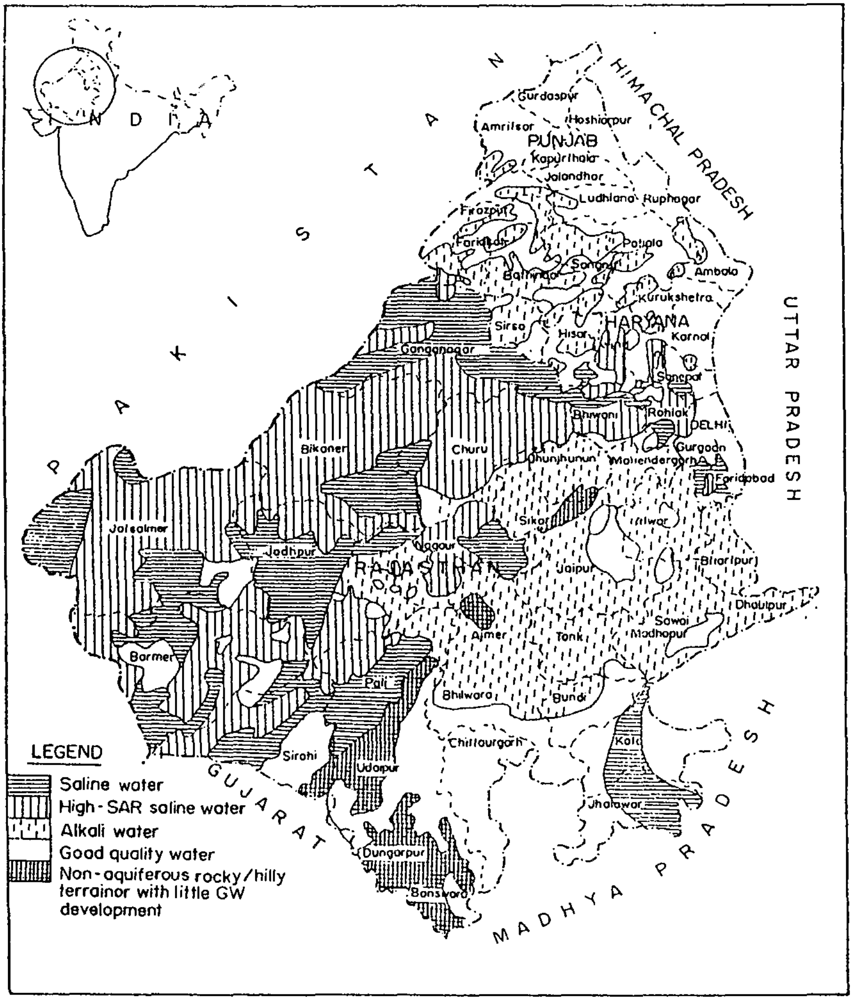


Fig. 2. Ground Water Quality in Haryana, Punjab, and Rajasthan.

The requirement for additional water supplies to increase the irrigation intensity from less than 100 percent to about 150 percent annually and the requirement of keeping the water table at a safe distance or reduction in disposable drainage volumes can, to same extent, be fulfilled by resorting to conjunctive use of surface and saline ground waters.

CONJUNCTIVE USE FOR SALINITY CONTROL

For surface water development alone, the water table in most irrigated areas would rise sooner or latter and waterlogging of the root zone would occur. There could be some limited situations where sub-soils are permeable and water table gradients are sufficiently steep to allow excess ground water to flow to other areas. With waterlogging, salt accumulates in the root zone because only pure water is utilized in evapotranspiration, leaving the salt behind.

In planning conjunctive use in a saline environment, two things are important. These are: (1) water table fluctuations and (2) river basin salinity balance. With conjunctive use of surface and ground waters, where a free hydraulic contact between the root zone and the sub soil water exists, this problem can generally be resolved over large part of the area, by lowering the water. In such a situation with conjunctive use, the maximum water level can be kept by design at some safer distance below the root zone. One can then maintain both water balance as well as salinity balance.

Conjunctive use however, does not permanently resolve the problem of salinity. It usually postpones this problem, maybe for decades. However, the salinity problem remains unless and until salts are transported out of the basin from each and every unit. Very few ground water storages allow for an adequate water flow rate to accomplish salt transport and maintain the levels of dissolved solids below acceptable level. The problem of root zone salinity materializes rapidly but the problem of the ground water basin takes more time to appear. It should be clearly understood that the root zone salinity problem is easier to resolve as compared to the ground water salinity. Positive actions have to be taken to restore salinity balance before the problem becomes irreversible. Larger basins reach the point of no return later in time than the smaller basins. An appropriate plan for maintaining the proper salt and water balance over the entire basin is an important element of conjunctive use planning which essentially requires transport of salt outside the basin. The salt flows with water, it means that a certain amount of annual ground water recharge will have to be thrown outside the basin. The quantity of the water to be thrown out will depend upon the concentration of the ground water. It was worked out by Srinivaslu et al (1993) that for part of the Lower Ghaggar Basin in Haryana (India) about 15% of the annual recharge would have to be thrown out of the system to maintain salinity balance at desired level.

TECHNOLOGICAL OPTIONS FOR GROUND WATER ABSTRACTION

There are various technical options available to abstract ground water/drainage water. Generally the water of relatively good quality is underlain by higher salinity ground water. Generation of drainage effluents would, therefore, involve manipulation of relatively fresh water without disturbing the deep saline waters. The possible technological options for drainage water abstraction may include: (i) several variations of vertical drainage and (ii) horizontal drainage.

Vertical Drainage

When aquifer formations provide favorable, vertical drainage through wells and tubewells as an efficient means of generating irrigation resource as well as producing drainage relief. Tubewells are relatively inexpensive to install and employ proven technology. Shallow tubewells which pump water from the first aquifer and cause larger draw-down per unit of water pumped are more suitable for lowering the water table. Experiences from Peoples Republic of China (You and Wang, 1983) and Pakistan (Chaudhary, 1992), and India (FAO, 1985) support this argument.

The possible variations of shallow wells for vertical drainage include (1) common filter and cavity tubewells (2) skimming wells and tubewells and (3) well points.

Cavity and Filter Tubewells

If water table control is the objective, filter tubewells are better alternative as compared to cavity tubewells. In filter tubewells, the well field for watertable control is so designed that average watertable is maintained at a preselected level. Well spacing, aquifer depths to be tapped and pumping rates are the important design considerations.

Skimming Wells

If it is desired to pump only the fresh water overlying the saline ground water, pumping from such aquifers has to be managed carefully. This requires special types of wells known as skimming wells. These may be tubewells or open wells. The design of these wells depends upon the thickness of fresh water aquifer, hydraulic properties, water table conditions and the discharge rates. A typical lithology where installation of skimming tubewells would be possible is shown in Fig.3.

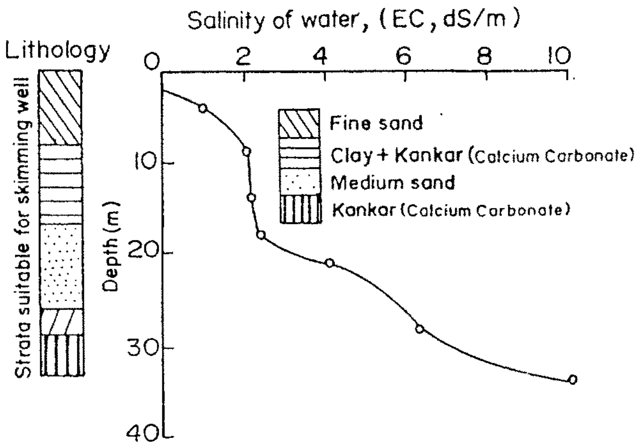


Fig. 3. Lithology and Water Quality of Bore Hole Suitable for Skimming Well. (Vill. Chiri, Rohtak, Haryana).

Studies were conducted at CSSRI to determine the rate of pumping at various penetration depths (Gupta and Tyagi, 1986) and it was concluded that for conditions prevailing in Ghaggar-Yamuna basin, skimming tubewells should be lowered for 50 percent penetration depth and for about 15 m^3/hr discharge. Skimming wells of 3-4 m diameter sunk up to 3.5-5.0 m depth were found useful in lowering the water table and in generating irrigation resource at Hisar (Kumar et al, 1990).

Horizontal Drainage

Where subsurface waters are relatively more saline, the water table remains above 2.0m for a considerable length of time and hydrogeological conditions do not permit the installation of tubewells, horizontal drainage can be effectively used to control waterlogging. Although the drainage water, to begin with, may be more saline, the salinity generally reduces with time. Because only first few meters of ground water flows towards horizontal drains in stratified soils, the system is more effective in skimming shallow ground water of fresh quality. The feasibility of horizontal drainage has been established through experimentation at several locations in North-West India (Rao et al, 1986). Based on cost optimization studies for a part of the irrigation system in North-West India, it was found that: (i) skimming wells and shallow tubewells are more cost effective in abstraction of drainage effluents, if hydrogeological conditions favoured their installation. (ii) it is possible to work out a scheme of operation that would permit reuse and thereby increase supply of water for irrigation and reduce the quantity of water required to be disposed through evaporation ponds or regional drainage network.

Assuming that it is technically feasible to intercept and pump the net annual recharge out of the irrigated area, it is necessary to determine an optimal mix of the technical alternatives that may be adopted in a given area. This could be achieved through model based on linear programming algorithms. A schematic diagram of the hydrological process is shown in Fig 4.

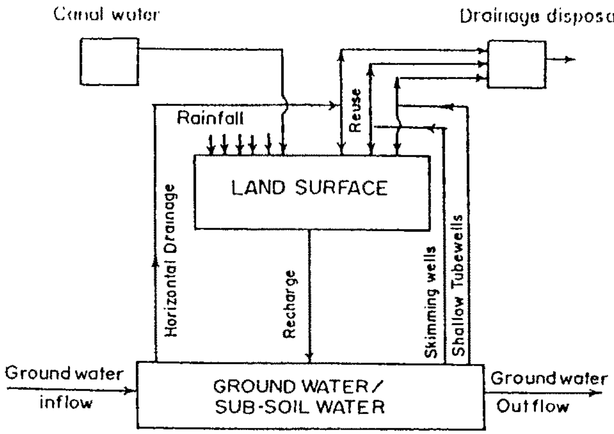


Fig. 4. Schematic Diagram of the Hydrological Process of Ground Water Abstraction and Reuse.

CONJUNCTIVE USE MANAGEMENT MODEL

Once the ground water quantity to be developed and its mode of development has been decided, the next step is to allocate water in conjunction with canal water. Such a model has been formulated by Srinivaslu et al (1997) to aid in planning strategies for water allocation and disposal so as to maintain salt and water balance in the crop root zone as well as the aquifer. The problem is treated as a non-linear optimization problem and a conjunctive use management model is developed. The schematic diagram of the process is shown in Fig. 5. The model allocates water to a number of crops according to their sensitivity to saline water so as to maximize net returns. The income is generated from disposal of crop produce while the cost is incurred in purchase of canal and tubewell waters. The non-water production inputs are treated as fixed costs. To keep the ground water salinity at the original level, part of the pumped ground water is disposed through evaporation ponds and has a cost. The allocations essentially center around crop-water-salinity production functions which are non-linear in nature.

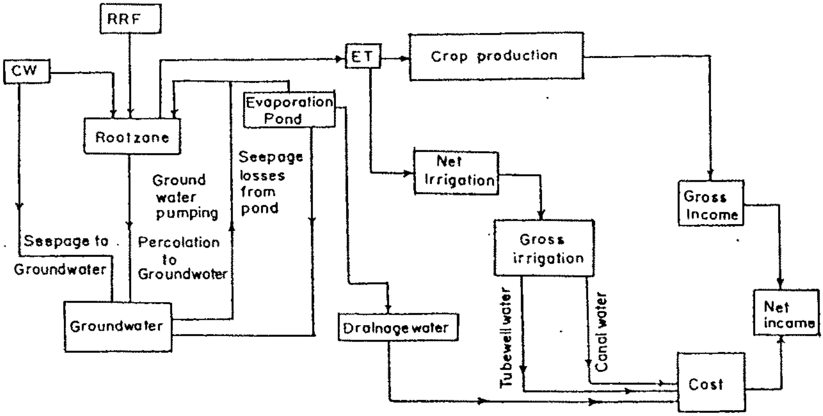


Fig. 5. Schematic Diagram of the Conjunctive Use Management Model.

The required production functions have been developed (Srinivasulu and Tyagi, 1993) with basic data on crop-water production functions and crop-applied water salinity production functions obtained from published and experimentally determined relationships (Tyagi 1980, Bhirud 1989). The two functions were synthesized into a single water-quality-quantity production function adapting the approach given by Letey et al. (1985). The required cost and benefit estimates for crop activities, canal water, ground water pumping and disposal etc., were developed using standard techniques of estimating and costing. The estimates of ground water in different water quality zones are based on water quality information from shallow tubewells which was subjected to analysis by the statistical software called 'GEO-EAS'.

The outputs from the model were cropping patterns, ground water disposal policies, total benefits and benefits per unit area/applied water.

SUSTAINABILITY OF SALINE GROUND WATER USE

Whereas it is possible to maintain the watertable at the prescribed level without ground water disposal by adjusting pumping, it is not a practice that can be sustained on a long term basis. In the absence of disposal, the salt load in the ground water reservoir will continue to increase and after some time, the negative effects of rise in ground water salinity will start appearing in the form of reduced yields and lower net benefits. In order to evaluate the level of ground water salinity at which the cost of disposal and benefits from increased availability of ground water without disposal will balance yield and income reductions, the model was run at various ground water salinity levels. The resulting benefits from water use without disposal were compared with benefits occurring with ground water disposal at various salinity levels (Fig. 6).

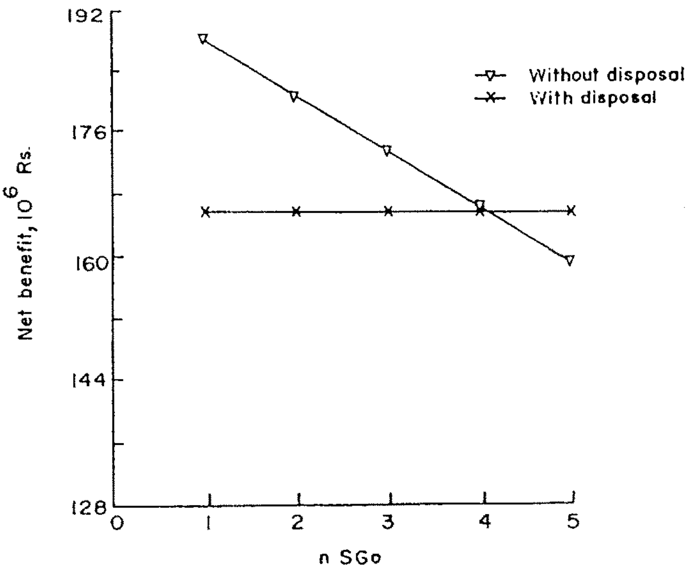


Fig. 6. Net Benefit With and Without Disposal of Various Levels of Ground Water Salinity (SG).

It may be seen that the benefits from optimization scheme without disposal were higher than benefits with disposal upto a salinity level nearly 4.1 times that of original salinity. It has several implications from the viewpoint of operation and management of saline ground water in conjunction with canal water. These are:

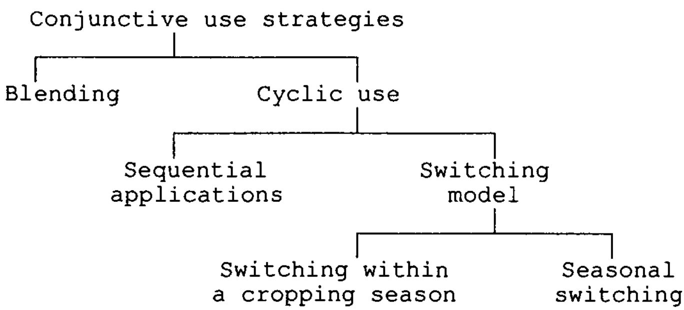
(1) Investment on disposal in the form of evaporation ponds can be deferred until such a time that the yield losses from increased ground water salinity nearly balance the cost of disposal. How long the investment can be deferred will depend upon the original salinity of the ground water, rainfall amount and its distribution, canal water quality and quantity.

(2) The level of investment in ground water disposal through evaporation ponds should be less than or equal to the annual reduction in net benefits.

(3) Whereas lowering the watertable and keeping it below critical levels is a necessary condition for sustainable conjunctive use of fresh and saline waters, it is not a sufficient condition. The sufficiency is provided by salt disposal only.

CONJUNCTIVE USE TECHNOLOGIES FOR MULTI-QUALITY WATERS

In conjunctive use, fresh and saline water is used in a manner that salinity of the soil would not exceed a pre-decided level so that the desired crop could be grown. In this strategy, a number of alternatives are available as shown in the following chart.



PRESENT STATUS OF CONJUNCTIVE USE IN NORTH-WEST INDIA

If we look around, we find very few examples of conjunctive use in the irrigation command. The only planned conjunctive use project that can be cited, as an example is the construction of augmentation tubewells in the Western Yamuna Canal Command in the state of Haryana. Construction of percolation tanks in the state of Karnataka and Maharashtra could also be cited in this context. However, major efforts have been voluntary and unplanned. In this category, one may cite the example set by the farmers in the states of Punjab, Haryana, Western Uttar Pradesh and the Maharashtra. As an example, one may look at the case of Haryana where joint use in areas with saline ground water has been picking-up over the years. More than 0.3 million ha area is being irrigated with saline waters covering a large zone in the irrigation commands. The increasing area under irrigation with saline water is also reflected in the number of minor irrigation structures that have tremendously increased during the last three decades. The increase has been both in the canal irrigated (more than 50% area irrigated by canals) as well as tubewell irrigated districts (more than 50% area irrigated by tubewells)(Table 2). The increased number of structures, has helped in arresting the rate of rise in water table to a certain extent.

A similar situation has been developing in the Mahi Canal Command in Gujarat particularly in areas underlain with ground water of EC < 3 dS/m. However, conjunctive use in the Ukai-Kakrapar command has not picked up because of the excess water available through the canals. A policy issue on the closure of the canal system during the hot season has been taken although the same is yet to be implemented.

In Rajasthan, conjunctive use of saline and fresh water has been limited as a result of ample water available through the IGNP canal in stage I. Moreover the ground water quality is poor in most of the stage I of IGNP. The Government of Rajasthan has proposed an incentive scheme to encourage conjunctive use of canal and ground waters. According to this scheme, sums of Rs. 282.6 lakhs are to be spent as incentive for the construction of about 1600 tubewells for this purpose.

Table 2. Progress of Minor Irrigation Units (Tubewells) in Haryana State.

District	Irrigated area by source (%)		District	Irrigated area by source (%)	
	Canal	Tube-wells		Canal	Tube-wells
Hisar	86	14	Panipat	28	72
Sirsa	84	16	Karnal	14	86
Jind	73	27	Gurgaon	13	87
Rohtak	68	31	Mahendragarh	7	93
Sonepat	67	33	Rewari	3	97
Kaithal	60	40	Kurukshetra	3	97
Bhiwani	58	42	Yamuna Nagar	3	97
Faridabad	36	64	Ambala	0	100

Source: Tanwar (1996)

SUMMARY

Conjunctive use of canal (fresh water) and ground waters in fresh water quality zones has been developed successfully in alkali affected areas. The development of ground water in these areas facilitated leaching and drainage leading to successful reclamation of alkali soils in Punjab and Haryana.

The conjunctive use in saline ground water areas with rising trend in water table is progressing gradually and there is need for refining the technology of ground water exploration in poor aquifers. Research on water application and scheduling to moderate the effect of poor water quality use on soil and crop health is also needed. In North-West India, the salinity balance can be maintained only if salts are disposed outside the region through a constructed drainage canal to the sea. Investigations on the techno-economic feasibility of this venture should be evaluated.

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AGRO-CLIMATIC RISK AND IRRIGATION NEED OF THE NILWALA BASIN, SOUTHERN SRI LANKA

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C.R.Panabokke[2]

ABSTRACT

Climate potential in respect to onset, magnitude and risk associated with rainfall for crop production in the Nilwala basin, Southern Sri Lanka was assessed using the daily rainfall of 12 stations scattered in different locations for more than 35 consecutive years (1950-1995). The program CROPWAT was used to assess the irrigation need.

It was revealed that rainfall of the basin increases from south to north with increasing elevation and altitude. Within a 70-km distance in the south north gradient, rainfall elevates from 1656 mm at Kekanadura to 4216 mm at Kudawa.

The net irrigation requirement of Yala rice in different locations varied from 1012 mm to 1246 mm. It was established that the irrigation need in the Nilwala upper catchment is below 40 % of the total water requirement, but in downstream areas it constitutes above 70% of the total water demand. Therefore both the Yala and Maha seasons in Nilwala downstream areas appeared to be unsuitable for rice cultivation without supplementary irrigation.

From April 10th onward until May 20th is the best period for establishment of perennial crops at upper catchment areas. Optimum dates for crop establishment at the mid and lower part of the catchment falls on the 14th meteorological week. It is important to note that delaying crop establishment in Yala by 2 or 3 weeks from the optimum date would result in a considerable increase of irrigation need even in the upper catchment areas; it is not advisable to delay the establishment of Maha rice until October when rice varieties of four month duration are cultivated.

INTRODUCTION

The Nilwala Ganga watershed is situated entirely in the Matara district, southern Sri Lnaka covering 960 sq. km. The river rises in the vicinity of Deniyaya at an altitude of 1050m and flows into the sea at Matara after traversing nearly 72 km.

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The rainfall of the basin increases from south to north with the increasing elevation and the altitude.

In respect of the rainfall pattern, the Nilwala upper catchment belongs to the wet and ultra-wet zones and the lower basin to the intermediate zone according to the climate classification of Sri Lanka.

There are five physiological regions in the basin; the flood plain (less than 6m above msl), the mantle plain (less than 50 m msl), highland region (50-300m msl) and the mountain region (300-1000 m msl). The climate gradient of the basin varies with the altitude gradient. In respect of agro-ecology, five agro-ecological zones, namely Wet zone Law country,2 (WL2), Wet zone Low country,4 (WL4), Wet zone Up country ,1 (WU1), Intermediate Low country, 2(IL2) and Wet zone Mid country,1 (WM1) zones are demarcated in the basin according to the agro-ecological map of Sri Lanka.

The present study deals with the rainfall probabilities and climatic water balance of the Nilwala watershed to improve the agronomy of the major crops grown in the basin with a particular emphasis on paddy and tea, which are the major crops grown in the area.

The major objective of the study is to identify optimum cropping calendars and planting times for major crops in different agro-ecological regions of the basin. This includes the ideal time for the commencement of tea and paddy while identifying the critical water deficit periods based on the water balance to provide supplementary irrigation.

When the genetic composition management and soil fertility level are at optimum, the ultimate growth and development of any crop is mainly governed by the weather regime. If a particular crop is considered, the limitation in climatic conditions to achieve high yields vary with the growth stage. Therefore, land use, cropping pattern and production schedules in a given geographical area are influenced by characteristics of rainfall and other climatic factors while influencing the farming operations besides crop growth.

Among climatic parameters in the tropics, rainfall shows the greatest spatial and temporal variations. There for the analysis of agro-climatic data in respect of a given amount of rainfall is extremely useful for agricultural operational planning. Studies in Sri Lanka by Parnabokke and Walgama (1974) have closely demonstrated that the arithmetic mean usually calculated directly from rainfall figures does not take into account the inherent skewness of the raw data that results from a large amount of rain falling in heavy tropical downpours thereby raising the mean level much above the normal amount of rainfall received or expected. Abeyasekara et al., (1983) have shown that the past attempts to use total or average values of rainfall for identification the best times for crop establishment has many inherent limitations such as lack of information on dry spells, etc. This is because the successful establishment of a crop depends not only on the soil moisture status at the time of planting but also on the length and repetition of dry periods during the crop season. Therefore the recommendations based on mean monthly averages may sometimes be hazardous as shown by Oldeman and Frere (1982).

It is worthwhile to consider the suggestions made by Krishnan (1980) to consider the week as the unit of time in the tropics where the rainfall is highly erratic in intensity, amount and distribution. This helps to take decisions based on the probability of receiving a certain amount of rainfall during a week to select crops and to identify the ideal time of planting while avoiding probable water stress periods and floods during sensitive phenological phases etc. This approach was widely used by Robertson (1976), Virmani (1980), and Virmani et. al., (1982) to characterise the agro-climatological potential in different locations.

MATERIALS AND METHODS

Daily rainfall data from 21 rain gauge stations in the Nilwala basin for the period of 1950-1995 were collected from the meteorological department for the analysis. However the continuous data were available for 12 stations (Table 1) which were selected for the analysis. Consistency of the data was assessed by the double mass curve and regression analysis for each pair of stations.

Within the Nilwala basin, actual pan evaporation data for a long period were available only at the university meteorological station, Mapalana. They were used to calculate potential evaporation for the locations situated at the Nilwala downstream.

The available data of average temperature and relative humidity of the Deniyaya station were used to calculate the potential evaporation for Nilwala upper catchment area using the Ivanov's model that has been tested for Sri Lanka in previous studies. (Weerasinghe, 1986)

The computer program "first" (Weerasinghe, Sabatier, Luc, 1990) has been used for rainfall probability assessment based on Markov Chain procedure. The computer programs BIL (developed at IRAT/CIRAD,Montpellier, France, (Franquin and Forest, 1982) and "CROPWAT" were used for computation of water balance and irrigation need.

RESULTS AND DISCUSSION

Annual and monthly rainfall statistics of the NILWALA rainfall: The locations of the rain-gauge stations, mean annual rainfall and the annual rainfall at 75 % probability levels are given in table 1.

Table.1 location of rain gauge stations and the annual rainfall

Station	Database	Latitude	Longitude	Altitude (m)	Mean Annual rainfall mm	Dependable .Rf (mm)#	Zone *
Kudawa	1980 -95	6.28'	80.25'	600	4216	2829	WU1
Anninkanda	1951-95	6.35'	80.32'	554	3867	2593	WU1
Panilkanda	1951-95	6.22'	80.38'	600	3092	2100	WU1
Arpthorp	1985 – 95	6. 13'	80. 20'	100	3246	2172	WM1
Mawarala	1951- 94	6.12'	80.35'	200	3041	2033	WM2
Hiyare	1951- 95	6.05'	80.20'	<30	2796	1867	WL2
Mapalana	1951- 95	6.03'	80.34'	58	2352	1567	WL2
Tihagoda	1951- 95	6.01'	80.34'	50	2041	1356	WL4
Kekanadura	1957- 92	5.58'	80.35'	<30	1656	1096	WL4
Charley Mount	1951-95	5.58'	80.28'	20	2527	1685	WL4
Dandeniya	1951-95	6.00'	80.39'	30	1686	1146	IL2
Denagama	1951-95	6.06'	80.39'	<30	1863	1236	IL2

* Agro-ecological zones as identified in the Agroecological map
\# At 75 % probability level

It is evident that the mean annual rainfall in Kudawa, Arpthorp and Anninkanda, exceeds 3810 mm and are in the ultra-wet zone according to the National Atlas (Agro-Ecology) of Sri Lanka. Mawarala, Hiyare, Panilkanda, Charley Mount and Mapalana receives greater than 2160 mm of rains, which is typical for the wet-zone. Thihagoda and Kekanadura come under the Wet zone Low country (WL4) according to the agro-ecological map. However with respect to dependable rainfall as well as annual rainfall, these two locations appeared to be much drier and are representative of IL2 zones as in the case of Dandeniya and Denagama stations.

Rainfall of the Nilwala basin increases from south to north with the elevation and altitude increase. The topography strongly influences the spatial distribution of rainfall, thus comparatively high rainfall is observed in the Deniyaya region. The dryness prevailing in the eastern part of the area is evident from the rainfall figures of the Dandeniya, Denagama, and Kekanadura stations. It appears that within a 70 km distance in a south - north gradient, rainfall elevates from 1656mm

(Kekanadura) to 4216 mm (Kudawa) and in a west -east gradient rainfall decreases from 2527mm (Charley Mount) to 1686 mm (at Dandeniya).

The dominant characteristics of the rainfall in all the locations are the bimodal rainfall distribution with two dry periods, one at January-February and second at July- August. Thus the rainfall pattern may be conveniently discussed in terms of Yala and Maha rains.

The rainfall year could be differentiated in to following cycles based on the types of rains received during the Yala and Maha seasons.

Months	**Yala season**	**Months**	**Maha season**
March - April	Convectional rains	Oct.-Nov.	Convectional rains
May - Sept	South-west Monsoon	Dec.-Feb.	North-east Monsoon

Table 2 indicates the average monthly rainfall at the different locations. According to Oldeman's (1980) criteria, wet months for rice would be a month with more than 200 mm rains and there should be at least three consecutive wet months in the season to cultivate wetland rice without irrigation. As experience reveals, the criteria of 200 mm may hold true for fluvial rice; it can be less for phreatic rice lands where lateral seepage of ground water occurs in areas such as the upper Nilwala catchment. Nevertheless water requirement for dryland crops could be met with an average monthly precipitation of about 90 mm. (Oldeman, 1980).

Table 2. average monthly rainfall (mm) at different locations of the Nilwala basin.

STATIONS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kudawa	171	117	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	177
Anningkanda	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	191	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Panilkanda	198	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	169	179	[redacted]	[redacted]	[redacted]	[redacted]
Arpthorp	115	87	180	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Mawarala	160	146	[redacted]	[redacted]	[redacted]	[redacted]	178	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Hiyare	133	140	190	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Mapalana	122	96	117	162	[redacted]	224	150	169	[redacted]	[redacted]	[redacted]	163
Tihagoda	71	54	91	176	[redacted]	212	171	[redacted]	[redacted]	[redacted]	[redacted]	116
Kekanadura	72	45	75	106	[redacted]	155	127	141	172	[redacted]	[redacted]	120
Charley Mont	95	75	109	175	[redacted]	[redacted]	147	155	[redacted]	[redacted]	[redacted]	149
Dandeniya	69	51	76	137	[redacted]	167	148	147	189	[redacted]	172	94
Denagama	107	94	124	146	[redacted]	161	114	110	163	[redacted]	[redacted]	172

It is evident from table 2 that in the upper Nilwala regions, the number of wet months with more than 200 mm in the annual cycle is 9-10 months and towards the flood plain, the number of wet months becomes considerably less. For instances, in Mapalana and Thihagoda, there are only 2 wet months in the Yala season and 3 to 4 wet months in the Maha season. Both Yala and Maha seasons in Dandeniya and Denagama seem to be not suitable for rice cultivation without supplementary irrigation. Minor tanks in the Nilwala basin are concentrated in WL2, WL4, IL1, and IL2 agro-ecological regions, which is a clear indication of the historical acceptance of irrigation water requirement in these areas, where rice could not be grown without supplementary irrigation.

Initial probability of rainfall: In a growing season of a given crop, a decision has to be made many times based on the probability of receiving certain amount of rainfall during a given week. A weekly rainfall of 10 mm at 75 % probability is considered in the present work as the sufficient level to satisfy the moisture requirement of the crops in three out of four years. This criterion is adopted by many authors in demarcating the wet and dry periods (Virmani 1976, Virmani et al 1982, Oldeman 1980).

Commencement of the Yala and Maha seasons in respect to the 10 mm rainfall limit at 75% probability at different locations are highlighted in the table 3. It is evident that the 10th to 50th meteorological weeks are wet in Kudawa. In Anninkanda, wet weeks in Yala and Maha seasons fall during the 9th to 29th and 35th to 52nd weeks. It is evident that the duration of the Yala season as well as Maha season is much shorter in Nilwala downstream and in the flood plain. It is worth noting the prevailing dryness in Denagama, Dandeniya, Thihagoda Kekenadura compared to Mapalana in both Yala and Maha seasons.

Optimum cropping calendar and planting time of rice: The optimum cropping calendar and planting time based on the water balance, calculated by "CROPWAT" for the rice in Yala and Maha seasons are given in tables 4 and 5. The optimum date of crop commencement was simulated by changing the date of planting and assessing the irrigation requirement. When cropping date is changed, the irrigation requirement is also changed, so the optimum date of planting was selected on the basis of the least irrigation requirement.

Table 3 Initial probability of weekly rains (Limit 10 mm)

Week	Kuda-wa	Annin-kan	Panik-anda	Arpth-orp	Mawa-rala	Hiyara	Mapal-ana	Tihag-oda	Kek'd-ura	Char-ley	Dand-eniya	Denag-ama
1	81	77	70	64	.53	63	51	40	28	51	27	51
2	68	77	77	61	63	65	63	54	42	63	54	60
3	56	70	75	41	56	39	46	30	33	48	38	54
4	62	59	75	54	60	63	44	35	17	44	38	49
5	44	68	75	45	56	51	51	30	36	51	40	39
6	56	61	70	50	49	51	40	40	19	46	32	44
7	56	66	65	52	60	53	40	37	42	41	22	47
8	31	70	77	59	74	63	46	30	33	51	41	53
9	63	86	83	56	63	72	53	49	33	61	38	49
10	75	82	73	63	67	67	51	30	25	56	22	60
11	94	86	85	66	76	74	58	19	28	54	35	56
12	56	95	95	57	79	67	62	43	28	61	54	53
13	88	93	90	64	81	79	49	54	31	44	57	56
14	88	95	80	66	88	74	72	57	55	76	57	74
15	88	84	73	66	74	76	60	59	42	59	54	70
16	100	95	88	80	86	86	74	68	50	85	59	84
17	100	95	88	89	95	86	84	76	61	78	62	77
18	82	91	93	86	90	81	77	76	75	78	73	67
19	93	86	80	84	86	81	74	70	69	76	67	67
20	100	89	80	86	83	83	77	62	72	78	81	65
21	94	91	72	82	88	81	74	68	64	78	70	81
22	94	91	75	90	86	81	81	68	81	83	76	86
23	94	86	75	91	88	84	88	70	69	87	73	81
24	88	79	75	89	86	84	76	73	72	78	62	67
25	94	84	80	89	77	79	72	65	72	76	68	72
26	88	86	85	75	74	72	74	81	78	76	73	63
27	88	75	58	70	70	67	65	62	67	73	65	56
28	94	81	65	84	81	81	74	59	69	83	54	74
29	88	81	65	80	65	72	65	54	64	76	59	63
30	81	70	65	77	60	74	70	56	58	66	65	56
31	81	68	60	73	72	67	65	51	42	59	65	51
32	88	79	65	75	74	70	63	78	64	73	54	67
33	75	73	63	73	74	70	63	70	69	66	57	60
34	81	68	73	63	63	72	58	54	53	59	59	49
35	87	75	70	70	70	74	63	59	53	61	68	63
36	69	82	68	64	65	60	58	51	53	68	57	60
37	75	81	80	77	79	76	77	70	61	78	70	67
38	88	84	78	86	86	91	77	70	64	83	81	72
39	88	86	73	86	81	79	83	81	75	83	70	74
40	88	84	70	80	76	79	74	70	69	73	73	70
41	88	86	85	5	79	67	79	65	69	88	78	72
42	88	84	85	80	79	72	81	70	72	83	76	79
43	88	84	88	82	88	74	76	86	75	93	81	81
44	94	95	85	89	93	74	88	81	89	93	86	98
45	94	95	83	89	86	72	81	76	92	88	81	95
46	94	100	85	84	88	81	91	78	83	93	7	93
47	81	86	83	73	88	81	84	73	75	80	73	86
48	69	89	80	77	83	81	79	65	69	80	57	81
49	88	93	88	70	88	74	84	62	53	71	49	91
50	88	80	78	59	70	65	63	49	44	61	35	63
51	63	89	70	61	88	70	67	49	58	71	35	67
52	50	93	83	79	81	79	63	59	58	76	54	74

Table 4. Irrigation requirement of Yala rice depending on the date of crop establishment.

DATE	Kudawa	Anninkanda	Panilkanda	Arpthorp	Mawarala	Hiyare	Mapalana	Tihagoda	Kekanadura	Charley Mount	Dandeniya	Denagama
Mar. 15	248	234	466	641	454	606	720	802	857	660	893	803
Mar. 20	205	213*	455	562	426	560	672	755	806	608	855	760
April 01	183	233	453*	456	411*	522	621	711	754	556	820	718
April 10	161	266	466	365	415	521*	607*	699*	736*	542*	808*	711*
April 20	145*	305	493	322*	437	565	639	729	760	575	824	747
April 30	144	360	530	333	471	630	694	782	806	633	854	806
May 10	145	413	566	364	505	691	744	835	849	692	887	866
May 20	145	462	599	396	540	742	787	886	884	750	923	922
May 30	160	509	630	443	573	782	822	930	914	802	957	970

- Optimum date of crop establishment for maximum rainfall utility

Table 5. Irrigation Requirement of Maha Rice depending on the date of crop establishment.

Date	Kudawa	Anningkand a	Panilkanda	Arpthorp	Mawarala	Hiyare	Mapalana	Tihagoda	Kekanadura	Charley	Dandeniya	Denagama
July 30	228	528	673	544	558	755	767	871	952	744	921	1074
Aug 10	200	468	621	482	494	684	691	817	898	676	880	998
Aug 20	354	413	580	450	439	663	668	798	882	646	866	923
Sep. 01	415	363	557	463	412	669	675	805	894	641	873	863
Sep. 10	473	345	531	483	417	690	696	825	914	653	894	820
Sep 20	530	357	500	503	437	724	729	859	938	681	930	820
Sep. 25	244*	230*	347*	376*	312*	606*	613*	744*	818*	563*	817*	699*
Sep. 30	592	389	465	532	474	770	773	905	969	724	974	843

* Optimum date of crop establishment for maximum rainfall utility

It is evident from table 4 that the optimum date for crop establishment at Kudawa falls on April 20th, since there would be sufficient rainfall until the 2nd week of August to meet the crop water demand. However it is worth noting that from April 10th onward until May 20th is the best period for crop as establishment at Kudawa. Analogically, dates for crop establishment at Nilwala upper catchment areas fall on March 20th at Anninkanda, April 1st at Paninkanda, April 20th at Arpthorp and April 1st at Mawarala areas.

The optimum dates for crop establishment at the mid and lower part of the catchment fall on 10th April. However it is worth noting the increment of irrigation water requirement in these areas compared to the upper catchment areas due to the prevailing dryness in lower and mid areas of the catchment.

In respect to the crop establishment in Yala season, one should keep in mind that delaying it by 2 or 3 weeks from the optimum date would result in a considerable increase of irrigation water need even in the upper catchment areas. Therefor, it is important to assure the establishment of the Yala crop before the Sinhala-Tamil New Year. This is the actual practice accepted by the farmers as experienced in many locations of the Nilwala areas and reported by Elkaduwa in 1997.

Optimum planting time for rice in Maha season.: It is evident from table 5 that Sep 25th is the optimum date of crop establishment for the Maha rice. This agrees with the results of the survey conducted by Elkaduwa (1997), by interviewing the farmers in the Nilwala upper catchment areas. According to the farmer's experience, the best period for crop establishment in Yala falls on April 10th and Maha in the latter part of the September.

It is evident that delay of cropping date beyond September 25th will result with the increase of irrigation water demand. Delay of the crop establishment will increase the water demand in January and February which are very dry at all the locations. As such it is not recommended to delay the crop until October when four-month varieties are cultivated.

Irrigation Requirement of Rice: Total water requirement, effective rainfall and the percentage irrigation demand from the total water need during the Yala and Maha seasons in different locations are given in tables 6 and 7.

In general the total water requirement of the Yala crop varies from 1012 - 1457 mm in different locations which agrees with the crop water need of rice under prevailing climatological situations in Nilwala areas. The irrigation requirement increases in the drier part of the Nilwala areas, which is associated with a decrease in effective rainfall. It is evident that irrigation need is below 40% in the Nilwala upper catchment, but it is considerably increases in the drier part. When the irrigation requirement exceeds 50% of the total, the risk will be very high. As indicated by the data, Dandeniya and Denagama have very high irrigation water demand, which constitutes above 70% of the total water demand. As such, rice in those areas cannot be cultivated if irrigation facilities are not provided.

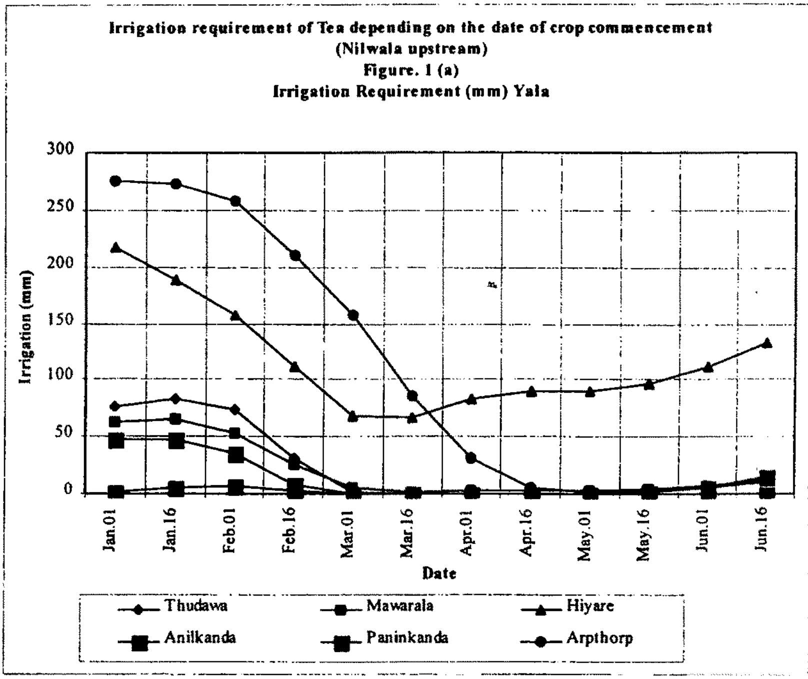
Table.6 Effective rainfall and Irrigation water requirement of rice during the Yala season

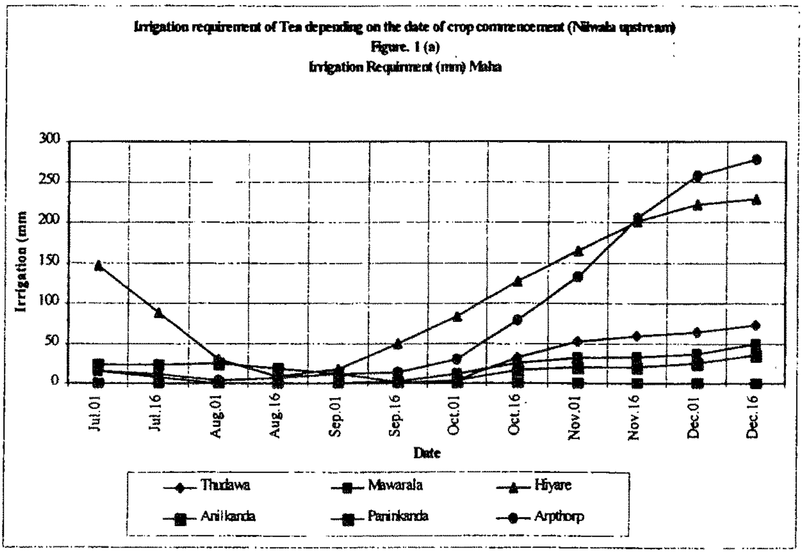
Station	Total water requirement	Effective rainfall	Irrigation requirement	Percentage irrigation requirement
Kudawa	1457	1293	164	11,25
Anningkanda	1085	872	213	19.63
Panilkanda	1042	589	453	43.47
Arpthorp	1070	748	322	30.09
Mawarala	1042	631	411	39.44
Hiyare	1016	494	521	20.22
Mapalana	1014	407	607	59.86
Tihagoda	1012	313	699	69.07
Kekanadura	1013	277	736	50.18
Charley Mount	1015	473	542	53.40
Dandeniya	1061	253	808	76.15
Denagama	1013	302	711	70.19

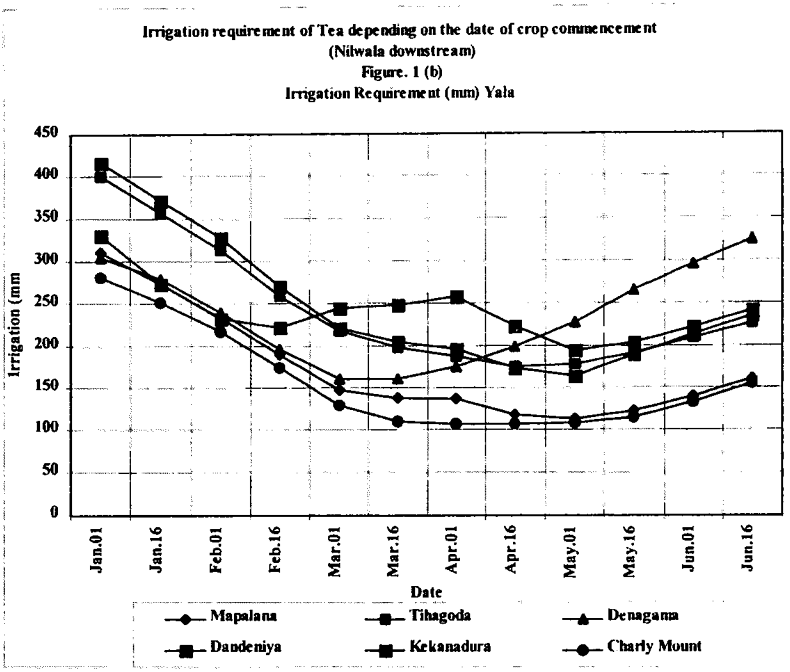
Table.7 Effective rainfall and irrigation water requirement of rice during the Maha season.

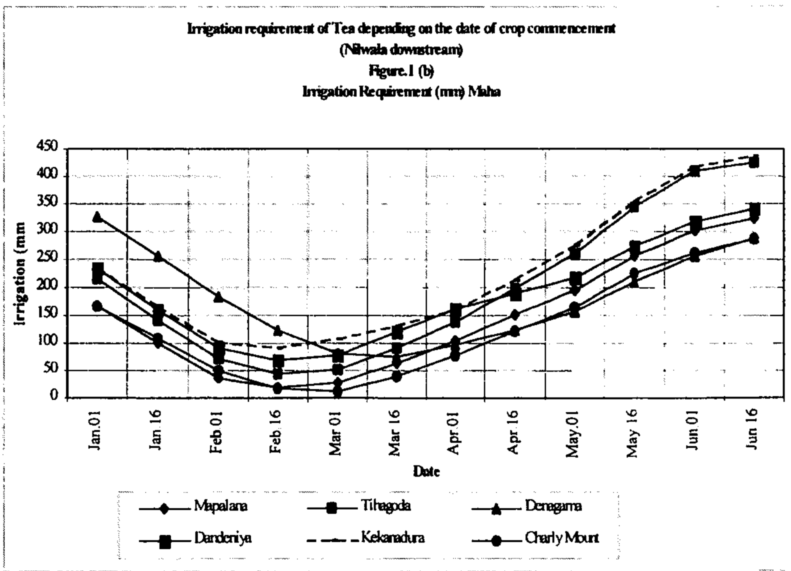
Station	Total water requirement	Effective rainfall	Irrigation requirement	Percentage irrigation requirement
Kudawa	1262	1018	244	19.38
Anningkanda	1175	945	230	19.5
Panilkanda	1042	695	347	33.33
Arpthorp	1201	825	376	31.30
Mawarala	1078	767	312	28.94
Hiyare	1143	537	606	53.01
Mapalana	1148	535	613	53.39
Tihagoda	1012	313	699	69.07
Kekanadura	1157	339	818	70.70
Charleymount	1148	584	563	49.04
Dandeniya	1155	338	817	70.73
Denagama	1163	464	699	60.01

Planting dates and irrigation requirement of tea and perennial crops: The most suitable dates for planting tea in the Nilwala areas based on the water balance is given in fig.1 (a,b)


Irrigation requirement of Tea depending on the date of crop commencement
(Nilwala upstream)
Figure. 1 (a)
Irrigation Requirement (mm) Yala
Irrigation (mm)
300
250
200
150
100
50
0
Jan.01
Jan.16
Feb.01
Feb.16
Mar.01
Mar.16
Apr.01
Apr.16
May.01
May.16
Jun.01
Jun.16
Date
Thudawa
Mawarala
Hiyare
Anilkanda
Paninkanda
Arpthorp


Irrigation requirement of Tea depending on the date of crop commencement (Nilwala upstream)
Figure. 1 (a)
Irrigation Requirment (mm) Maha
Irrigation (mm
300
250
200
150
100
50
0
Jul.01
Jul.16
Aug.01
Aug.16
Sep.01
Sep.16
Oct.01
Oct.16
Nov.01
Nov.16
Dec.01
Dec.16
Date
Thudawa
Mawarala
Hiyare
Anilkanda
Paninkanda
Arpthorp


Irrigation requirement of Tea depending on the date of crop commencement
(Nilwala downstream)
Figure. 1 (b)
Irrigation Requirement (mm) Yala
450
400
350
300
250
200
150
100
50
0
Irrigation (mm
Jan.01
Jan.16
Feb.01
Feb.16
Mar.01
Mar.16
Apr.01
Apr.16
May.01
May.16
Jun.01
Jun.16
Date
Mapalana
Tihagoda
Denagama
Dandeniya
Kekanadura
Charly Mount


Irrigation requirement of Tea depending on the date of crop commencement
(Nilwala downstream)
Figure.1 (b)
Irrigation Requirement (mm) Maha
450
400
350
300
250
200
150
100
50
0
Irrigation (mm
Jan.01
Jan.16
Feb.01
Feb.16
Mar.01
Mar.16
Apr.01
Apr.16
May.01
May.16
Jun.01
Jun.16
Date
Mapalana
Tihagoda
Denagama
Dandeniya
Kekanadura
Charly Mount

The water balance is calculated using the program CROPWAT considering the requirement of a wet period for 120 days for the crop to establish the root system. Rooting depth was considered as 45 cm at the planting time and 60 cm at the latter stages. The accepted soil moisture depletion level was taken as 75%.

Results of the simulation revealed that there will be no irrigation requirement if the planting was done during March 15th to May 15th in Kudawa, Anningkanda, Panilkanda and Mawarala. However in Arpthorp the suitable period falls within April15th to May 15th. It is not advisable to delay the planting date beyond May 15th in all the locations of the Nilwala upper and mid catchment areas. However in Hiyara the best time for planting would be around March 15th with an irrigation requirement of about 75 mm.

For most of the locations in the Nilwala upper and mid catchment areas, establishment of the crop in Maha seems to be not advisable due to the dry spells in January-February. However at Kudawa, Paningkanda and Anningkanda the crop may be established during Sep 1st - October 1st. (Fig.1 a)

In the flood plain and the lower regions of the Nilwala river, the best crop establishment period with least irrigation water requirement falls during the mid-August to mid-September. If the crop could be established during this period, the irrigation requirement prior to root establishment will be low.

From the water balance point of view, it could be concluded that the best period for crop establishment in the Nilwala upper and mid catchment areas falls before May 15^{th}. In the lower flood plain, it falls before September 15th.

CONCLUSIONS

Rainfall of the Nilwala basin increases from south to north with the increasing elevation and altitude. The topography strongly influences the spatial distribution of rainfall and comparatively high rainfall is observed in the head waters of the Nilwala river at Deniyaya region. Within a 70 km distance in the south north gradient, rainfall elevates from 1656 mm (at Kekanadura) to 4216mm (at Kudawa). In the west east gradient, rainfall decreases from 2527 mm at Charley Mount to 1686 mm at Deniyaya.

The upper mountainous region of the Nilwala basin has 9-10 months with more than 200 mm monthly rains in the annual cycle where high probabilities exist to receive more than 200 mm monthly rain during both the Yala and Maha seasons.

During both the Yala and Maha seasons in Nilwala, the downstream areas seem to be unsuitable for rice cultivation without supplementary irrigation. Minor tanks for irrigation purposes in the Nilwala basin are concentrated in WL2, WL4, IL1, and

IL2 agroecological regions, which is a clear indication of the historical acceptance of the necessity for irrigation in the downstream areas.

From April 10th onward until May 20th seems to be the best period for establishment of crops at the Nilwala upper catchment areas. Optimum time for establishment of rice falls on March 20th at Anningkanda, April 01st at Panilkanda, April 20th at Arpthorp, and April 1st at Mawarala. Optimum dates for crop establishment at the mid and lower part of the catchment falls on April 10th.

In respect to the crop establishment in the Yala season, it is important to note that delaying it by 2 or 3 weeks from the optimum date would result in a considerable increases in irrigation water need even in the upper catchment areas. Therefore it is important to assure the establishment of the Yala crop before the Sinhala-Tamil New Year.

This is the actual method practised by farmers as experienced in many locations of the Nilwala areas. With respect to the Maha season, it is not advisable to delay the establishment of crop till October when four month varieties are cultivated.

The total water requirement of Yala rice varies from 1012 to 1267 mm in different locations of the Nilwala basin. The irrigation requirement increases in the flood plain, which is associated with a decrease in effective rainfall. Deniyaya and Denagama have a very high irrigation demand, which constitutes above 70% of the total water requirement. As such, these are high-risk areas of the Nilwala basin for rice production.

There will be no irrigation requirement for tea and other perennial crops if the planting is practised during March 15th to May 15th in Nilwala upper and mid catchment areas. Establishment of tea in Maha seems to be not advisable due to the dry spells falling on the January and February months. However, at Kudawa, Panilkanda and Anningkanda tea may be established during September 1st to October 1st of the Maha season.

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WATER BALANCE AND THE IRRIGATION NEED OF RICE IN DIFFERENT AGRO ECOLOGICAL REGIONS OF SRI LANKA

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J.L. Sabatier[2]

ABSTRACT

Daily rainfall and pan evaporation in 22 locations of Sri Lanka for more than 35 consecutive years were analyzed to assess the Agro climatic potential of different regions in respect to moisture availability, for which the computer program "first " was developed . In the program Markov chain procedure is employed to analyze dry and wet spells; forward and backward rainfall accumulation probability curves are incorporated to decide upon the crop establishment time and the point at which two curves are bisected was considered as the probability at which the particular crop could be grown. Water balance of the localities were assessed using the Hargreave's Moisture availability index (MAI) and Troll's criteria. The program CROPWAT was used to estimate irrigation need to plot the rainfall, evaporation, water balance, crop performance probability and irrigation need maps.

From the stand point of the water balance approach for Yala and Maha seasons two hydrologic regions, namely humid and semi-arid regions are identified for the Maha season (fig.3) and three hydrological regions viz. Humid, Semi-arid, and Arid regions, in Yala season. The entire dry zone remains arid in the Yala season (Fig.4) Crop commencement in these regions could be done in 42nd - 43rd weeks.

Performance probability of rice in the "Maha" season appeared to be lowest in Hambantota and Puttalam, and highest at Batticaloa, Trincomalee and Polonnaruwa areas. It was established that irrigation need in Maha and Yala seasons as 597-1000 mm, (except Hambantota area) and 1200-1300 mm.

INTRODUCTION

Sri Lanka is a tropical island with an area of 65610 sq. km, where the double cropping of rice is practiced for centuries using the rainfall of north-east and south -west monsoons. The monsoon regime demarcates two distinct seasons for cropping practices namely "Maha" (major) and "Yala" (minor) seasons.

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The minor season doesn't carry sufficient moisture for a pure rain fed crop in many parts of the island. Thus in respect to the rainfall distribution pattern, Sri Lanka is divided into wet, intermediate, and dry zones which are further sub-divided into 21 agro-ecological zones. Accordingly eleven agro-ecological regions have been identified for the wet zone, four in the intermediate zone and six in the dry zone (National Atlas of Sri Lanka)

The wet zone covers 1.54 mln ha, where annual precipitation ranges from 2300-5100 mm. The intermediate zone is spread over 0.85 mln ha where annual rainfall is 1600-2300 mm. The major part of the island is covered by the dry zone (4.17 mln ha) where annual rainfall ranges from 900-1500 mm.

Present agricultural policies of the government are geared to settle the farmers in the north-central and eastern dry zones with the aim of intensifying paddy cultivation by means of irrigation in the additional land of 364200 ha and 60000 ha in north-central and south-eastern dry zone respectively. It is also envisaged to increase the rice production up to 4.5 t/ha in the long term by expanding water management programs (National policy frame work, 1995). Therefore the realistic estimates of the water need for rice irrigation, suited to the Agro - Pedo- Climatological potential of dry areas is of paramount need to meet the future challenges in rice intensification programs.

Correct assessment of water need, onset and duration of the season and risk associated with dry and wet spells are important aspects in this regard.

The objective of the present paper is to assess the moisture availability and the agro-climatological risk in different agro-ecological regions for rice farming. An attempt was made to identify the different hydrological regions of the country based on water balance.

MATERIALS AND METHODS

Daily rainfall and pan evaporation of 22 locations in the dry, intermediate and wet zones, which represent all agro-ecological regions of Sri Lanka were used for the present analysis. The geographical locations, annual rainfall and pan evaporation of the selected locations are given in table 1.

Table.1 Annual rainfall (1950-1990) and the respective Agro-ecological zones of the selected stations.

Station	Long	Latitude	Rainfall (mm)	Agro-ecological zone*
1. Anuradhapura	80.27	8.20	1282	DL1
2. A'pelessa	80.90	6.15	1092	DL1
3. Badulla	81.05	6.99	2384	IM1
4. Batticaloa	81.70	7.72	1765	DL2
5. Charley Mount	80.28	6.00	2761	WL4
6. Colombo	79.86	6.90	2345	WL4
7. Dandeniya	80.39	6.00	1724	WL2
8. Denagama	80.79	6.06	1903	IL1
9. Hambantota	81.13	6.12	1041	DL5
10.Jaffna	80.02	9.65	1213	DL4
11. Kalawewa	80.35	8.00	1120	DL1
12.Maha luppallama	80.47	8.12	1379	DL1
13. Mannar	79.92	8.95	958	DL3
14. Mapalana	80.57	6.07	2354	WL2
15. Mawarella	80.36	6.11	3067	WL1
16. Nuwara Eliya	80.77	6.97	2328	WU3
17. Polonnaruwa	81.00	7.93	1669	DL1
18. Puttalam	79.83	8.03	1226	DL3
19. Thihagoda	80.34	6.01	1830	WL4
20. Trincomalee	81.21	8.58	1522	DL1
21. Vavuniya	80.50	8.57	1420	DL1
22. Watawala	80.60	6.95	5241	WU1

A computer program named "first", was created (Weerasinghe, Sabatier Grandgean Luc, 1990) to assess the rainfall probabilities and statistics at a desired level in monthly, weekly ten-day or five-day periods. The rainfall probability of the period is calculated by the ranking order method. The program allows probability levels to be selected by the user. Probability of rains in monthly and weekly intervals at 75% probability were taken as the assured rains in the present study.

In the program, the Markov chain procedure is employed to analyze dry and wet spells; the method of backward and forward accumulation described by Morris and Zandstra (1979) is incorporated to calculate onset and termination of the rainy season. By choosing a certain date during the calendar year, usually the peak of the dry season, the rainfall of the selected period could be summed forward or backward until a certain amount is accumulated. This process is repeated for all years of the data file and the probability of having received given amount of rain can be given for each time interval chosen.

As suggested by Morris and Zandrsta (1979), 75mm accumulation of rainfall at the 75% probability was taken as the onset time for the growing season for dry seeded crops, and 200mm accumulation for wetland preparation of rice.

The termination of the wet season is determined by the backward summing of rainfall data. According to Morris and Zandstra (1979), 500mm of accumulated rains after the planting would be sufficient to raise wetland rice. This criteria is used by Oldemen and Frere (1982), to determine the onset and termination of rice growing seasons in South East Asian countries.

In the present work, forward and backward moisture accumulation curves were employed to decide upon the crop establishment period and the satisfaction of the rainfall to meet crop water demand. The probability level at which two curves of a given crop is bisected is considered to be the probability at which the particular crop could be raised (crop performance probability).

Forward accumulation of 200 mm rains from March 1st for Yala and September 1st for Maha seasons, and the backward accumulation of 500 mm rains from July 1st and September 31st for two respective seasons were computed. Based on those accumulations crop performance probability of the rice was assessed.

Water balance of the localities were assessed using the Hargreave's (1971) moisture availability index (MAI). The Program CROPWAT was used to estimate irrigation need to eliminate the climate risk in both Yala and Maha seasons. Irrigation requirements of rice for the different locations were simulated considering the transplanted paddy in LHG soils. The GIS program UNIMAP was used to plot the rainfall, evaporation, water balance, crop performance probability, and irrigation need maps.

RESULTS AND DISCUSSION

The rainfall map clearly demonstrates that Sri Lanka has number of rainfall zones. The central mountainous region against the south-west winds during the wet monsoon makes a clear climatic divide. High precipitation areas are found along the windward slope of the south-west monsoon. The sharp contrast to the leeward side is clear. Most arid regions lie in north-eastern and south-western boundaries of the country (fig.1). The highest evaporation 2400 – 2500 is observed in Trincomalee. The other parts of the dry zone have an annual evaporation over 2100 mm.

The number of consecutive months with Moisture Availability Index (MAI) above 0.34 in the annual cycle and in the Yala and Maha seasons are given in fig 2,3 and 4 (Weerasinghe, 1991)

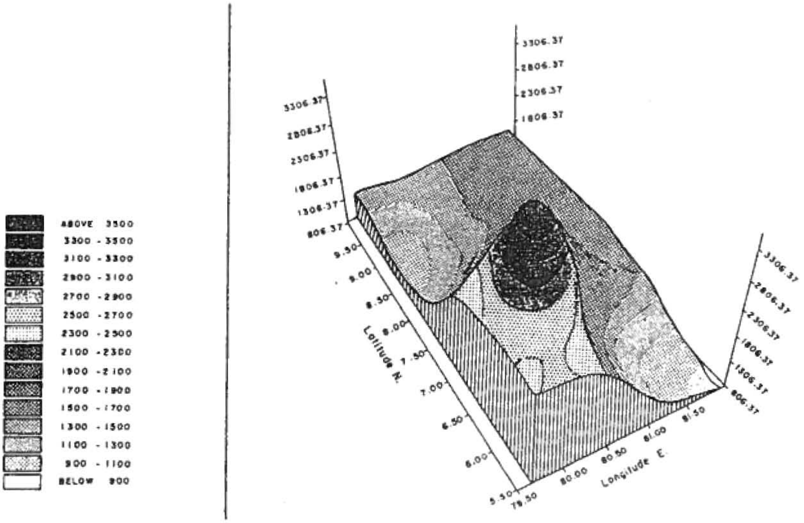


Figure 1. Annual Rainfall – Sri Lanka (mm)

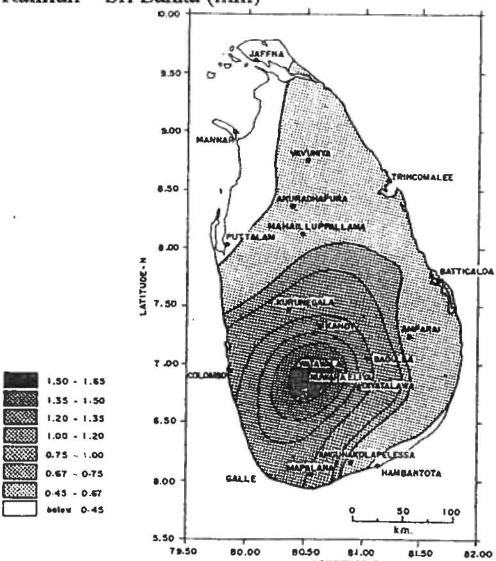


Figure 2. Annual Moisture Availability Indices (MAI),Sri Lanka according to Hargreave's Classification

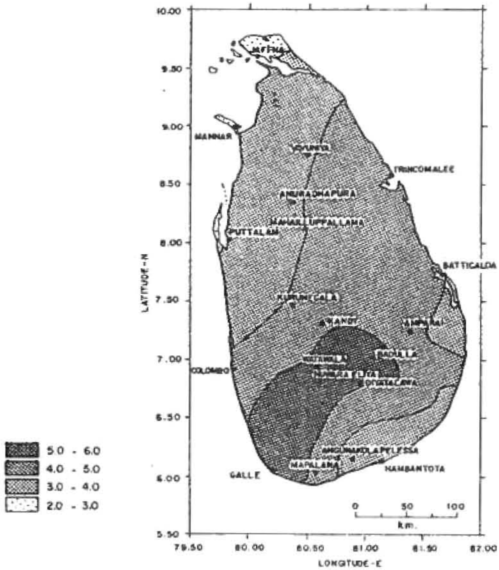


Figure 3. Number of Consecutive Months with MAI above 0.34 in Maha Season

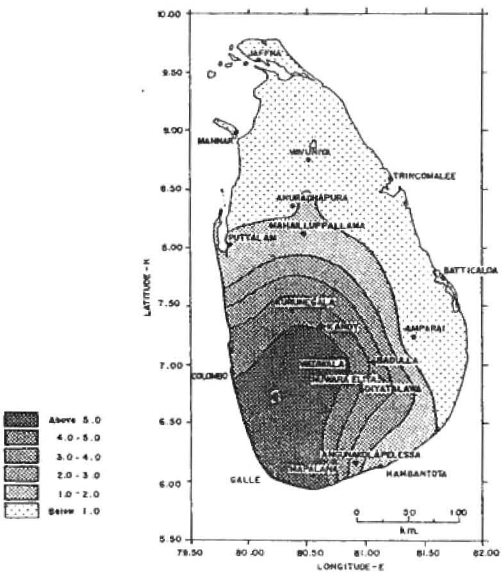


Figure 4. Number of Consecutive Months with MAI above 0.34 in Yala Season

According to annual MAI, part of the dry and intermediate zone of Sri Lanka could considered to be in moderately deficient moisture regions. However Jaffna, Mannar, Puttalam, Trincomalee, Amparai and Hambantota areas have less moisture availability, compared to other moisture deficient regions.

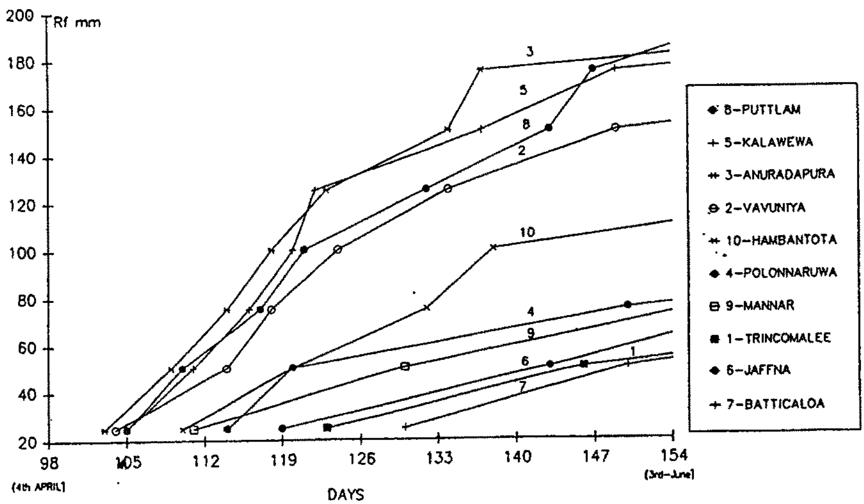
From the stand point of the water balance approach for Yala and Maha seasons, two hydrologic regions namely humid and semi-arid regions are identified for the Maha season (fig.3) and three hydrological regions viz. Humid, semi-arid and Arid regions, in Yala season. The entire dry zone remains arid in the Yala season (fig.4)

The selection of proper sowing dates constitutes the central strategy in the optimum exploitation of the rainfall resources. According to Panabokke and Walgama (1974), the main strategy in selection of cropping season is to tailor the crops to rainfall, and adjust their management to available sequence of soil moisture.

Farmer's cropping strategies are influenced by the variability they have experienced in the onset of the cropping season. This could be examined by judging the forward rainfall accumulation probabilities from the date of the commencement of the rainy season.

Dates that the forward accumulation of 25 to 200 mm rains from the beginning of the Yala and Maha seasons (from March 1st and September 1st) at ten selected stations in the dry areas of the country are at 75% probability level are given in figures 5 and 6.

FORWARD ACCUMULATION OF RAINFALL AT THE BEGINING OF 'YALA' SEASON IN 3 OUT OF 4 YEARS(.75P) FIG 5



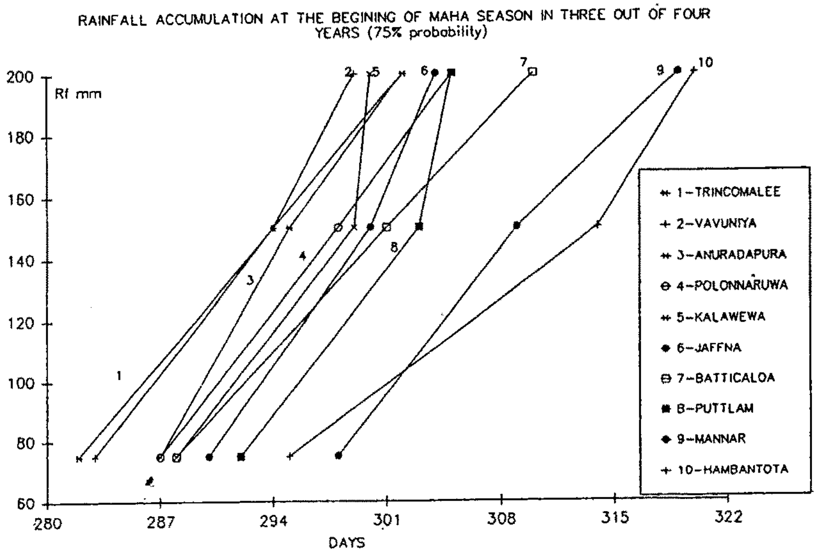


Figure 6.

In three out of four years, 200 mm rainfall accumulation which is needed for wetland preparation in Maha could be expected in the 42nd to 43 rd weeks in all locations except Hambantota and Mannar where accumulation is delayed by about two weeks (fig. 5) Accumulation of 75mm rainfall for dry land crops in Maha could be expected in Trincomalee and Vavuniya on the 41st week which is about one week earlier than Anuradhapura, Polonnaruwa, Kalawewa, Jaffna and Batticola, and two weeks earlier than Hambantota and Mannar. This agrees with the earlier findings of Panabokke and Walgama (1974), where authors have identified the sowing dates for southern wet zone around the 41st week and for the area around Hambantota and Thissamaharama approximately 7 to 10 days later.

In our earlier work we have shown that in the sufficient moisture regions for wetland rice, the forward and backward moisture accumulation curves of 200 and 500 mm meet at a level above 75% probability. Where rainfall is inadequate the two curves meet at a low probability level (Weerasinghe 1989) Furthermore in order to achieve the possible probability, the crop has to be sown prior to the date indicated at the meeting point of the two curves. Table 2 indicates the crop performance probabilities and latest date of crop commencement at different locations of the dry areas. Probability map of the Maha rice crop is given in fig 7.

Table 2. The performance probability of the rain fed Maha rice in Dry Areas

Location	Probability of Maha crop	Last date of Crop Commencement (Week)
1. Batticaloa	75	45
2. Trincomalee	75	43
3. Polonnaruwa	70	44
4. Jaffna	70	43
5. Kalawewa	65	43
6. Vavuniya	60	43
7. Anuradhapura	55	42
8. Mannar	40	43
9. Puttalam	40	42
10.Hambantota	18	42

It is evident that the probability of Maha rainfed rice exceeds 75% in Galle, Colombo, Kandy Nuwaraeliya and Rathnapura areas. Analogicaly success is above 70% in Kurunegala, Polonnaruwa, Trincomalee and Batticloa areas. In rest of the country performance probability of rice seems to be lie around 50% except Hambantota and Puttalam which are the driest of the country (Fig.7).

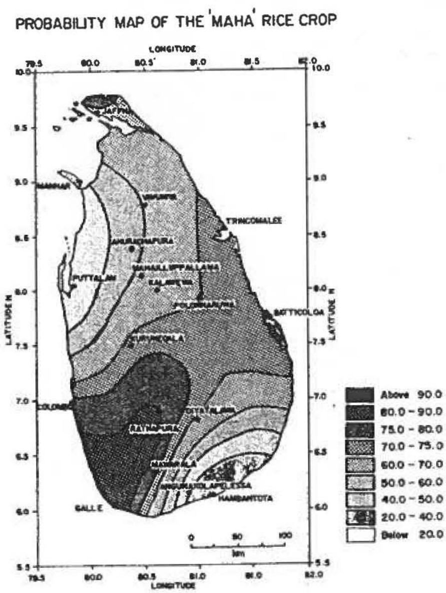


Figure 7.

The Irrigation Requirement of Rice as calculated by the program "Cropwat" varies from 1200-1500 mm in Yala season and 597-1000mm in Maha season except Hambantota where the irrigation demand is around 1200-1300 mm (Fig. 8 and 9).

IRRIGATION NEED OF THE 'YALA' RICE IN NORMAL YEARS

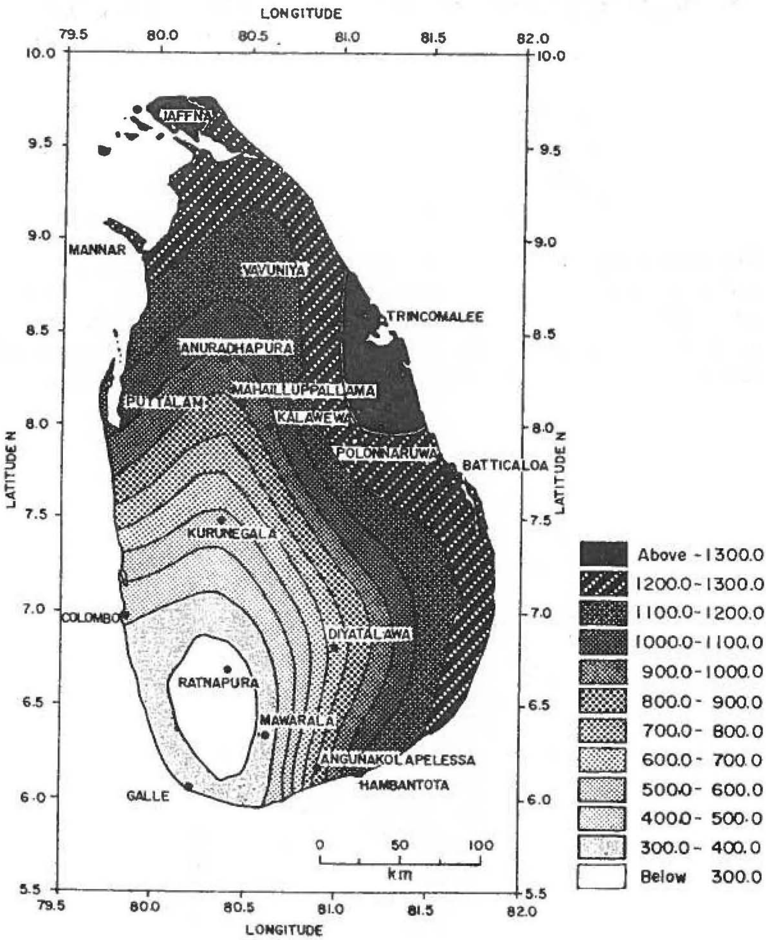


Figure 8.

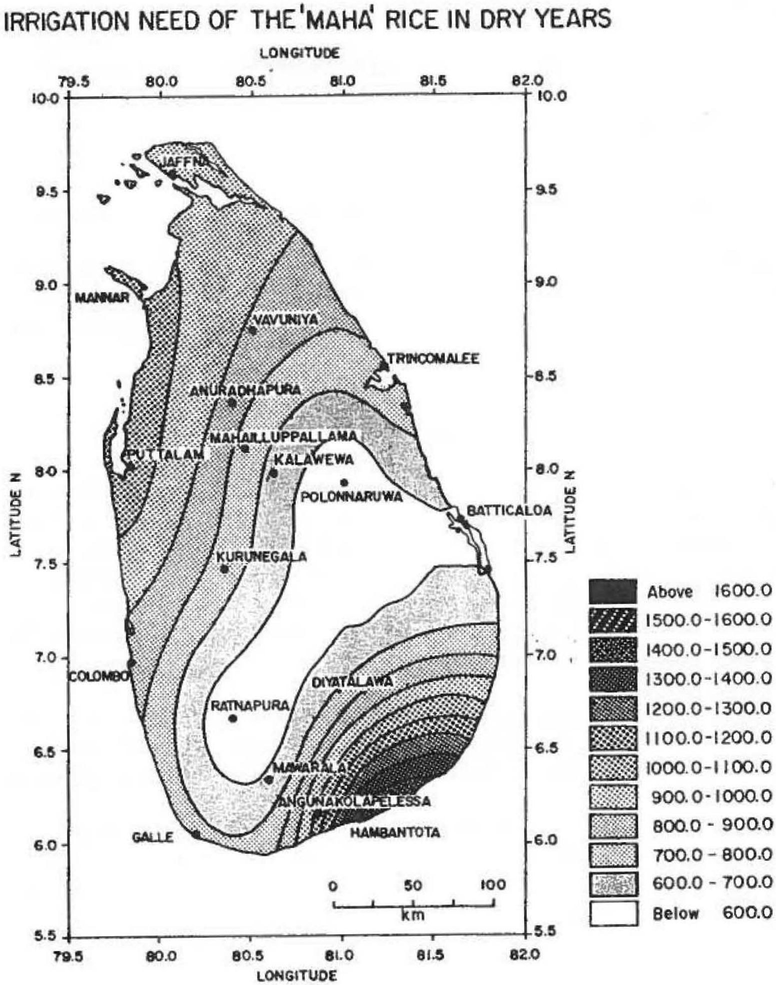

IRRIGATION NEED OF THE 'MAHA' RICE IN DRY YEARS
LONGITUDE
LATITUDE N
JAFFNA
MANNAR
VAVUNIYA
TRINCOMALEE
ANURADHAPURA
MAHAILLUPPALLAMA
PUTTALAM
KALAWEWA
POLONNARUWA
BATTICALOA
KURUNEGALA
COLOMBO
DIYATALAWA
RATNAPURA
MAHARALA
ANGUNAKOLAPELESSA
HAMBANTOTA
GALLE
0 50 100
km
Above 1600.0
1500.0-1600.0
1400.0-1500.0
1300.0-1400.0
1200.0-1300.0
1100.0-1200.0
1000.0-1100.0
900.0-1000.0
800.0 - 900.0
700.0 - 800.0
600.0 - 700.0
Below 600.0

Figure 9.

It is clear that Maha irrigation need is much less in north-east and north-central dry zones compared to other dry areas. Low irrigation need in many locations in the November / December period coincides with the availability of sufficient amounts of rainfall from the north-east monsoon. However irrigation need in Hambantota is more than doubled that of Batticola and Polonnaruwa in Maha season. This associates with the comparatively high dryness in Hambantota even in the Maha season.

Present analysis indicates high water need and risk associated with rice production in Hambantota, Mannar, and Puttalam areas where the irrigation systems may have to supply more water during the Maha season. The rehabilitation of abandoned tanks, proper water management, and adaptation of timely crop practices and water conservation by minimizing the wastage are some of the practical measures to be taken to minimize the high irrigation need in different locations.

CONCLUSIONS

The dry zone of Sri Lanka can be differentiated into two distinct hydrological regions according to Hargreave's MAI namely, "moderately deficient" and some what deficient moisture regions. From the stand point of the water balance approach for Yala and Maha seasons, two hydrological regions, namely humid and semi-arid regions can be identified for the Maha season, and three hydrological regions viz.humid, Semi-arid, and Arid regions, in Yala season. The entire dry zone remains arid in the Yala season.

In most locations of the dry zone, forward accumulation of 200 mm rains for the commencement of the wetland rice in Maha at 75% probability level could be expected on 42-43 weeks with an exception of Puttalam and Hambantota areas.

The highest irrigation need in Maha seems to be in the Hambantota (1000-1200 mm) district followed by Puttalam and Mannar. The irrigation requirement at Yala accounts for 1200-1500 mm in the northern dry zone and 900-1000 mm in the north-central dry zone.

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APPLICATION DEPTH UNDER SPRINKLE IRRIGATION AS AN ECOLOGIC AND ECONOMIC FACTOR

Nickolai S. Yorkhov*

ABSTRACT

For most natural conditions, the pre-runoff application depths (PRADs) under sprinkle irrigation are considerably less than the maximum application depths required to moisten active root zone from a critical soil water content to field capacity. Increasing the PRADs to some extent or up to the maximum application depth may prove to be an expensive activity. To justify such an activity, a thorough comparative economic analysis should be made involving various measures for increasing the PRADs and accordingly the actual application depths. Such an analysis becomes possible only if we know the influence of application depths on economically important parameters of a farm sprinkle irrigation system. Influence of application depths on the properly irrigated area, energy used for moving the sprinkle systems, and soil water evaporation is discussed in the paper.

Sustainable development of mankind is known to be an imperative of our time. Such a development envisages rational use of natural resources, to include mainly ecologic safety and economic optimum for any useful activity of man. That principle remains intact in relation to agriculture and to irrigated agriculture in particular.

The main ecologic problem of sprinkle irrigation is water erosion of the soil, that is irrigation erosion. It occurs when there is surface runoff of irrigation water during a watering process. Runoff results not only in soil erosion but in other detrimental ecologic and economic consequences as well.

To solve that problem many scientists recommend using criterion of allowable application rate. However that criterion proved to be inapplicable for solving the above mentioned ecologic problem. Based on the concept

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of rational use of natural resources, the allowable application rate criterion does not allow a proper economic optimization of the erosion-safe sprinkle irrigation technology for a given setting of physical and economic conditions in which an irrigation system is to be constructed or reconstructed. The only proper criterion to be used for such a purpose is the pre-runoff application depth.

To ensure ecologic safety and economic efficiency of sprinkle irrigation, it is necessary that actual amounts of water applied per watering (per irrigation), actual application depths m, match the following conditions

$$m \le m_o \text{ (if } m_o \le m_m\text{)}, \quad (1)$$
$$m \le m_m \text{ (if } m_o > m_m\text{)}, \quad (2)$$

where m_o = pre-runoff application depth;
m_m = maximum application depth.

Pre-runoff application depth is the maximum application depth which does not cause surface runoff and subsequently soil erosion during a watering process by a sprinkle system at a given field or plantation. Pre-runoff application depths change in the course of an irrigation season subject to seasonal changes in soil aggregate stability, plant cover of the soil, and other factors. Maximum application depth is a quantity of water required to moisten the active root zone, where most plant roots are available, from a critical water content to field capacity. Condition (1) ensures erosion safety of the sprinkle irrigation as well as prevents water loss through surface runoff whereas condition (2) extinguishes water loss through deep percolation. For most soils except those with very light sandy texture, the common case is the situation when the maximum application depths far exceed the pru-runoff ones,
that is $m_o << m_{max}$.

In many instances the pre-runoff application depths appear to be too small to meet some economic, operational and technical requirements. So a problem arises to increase the pre-runoff application depths. A great number of various measures suitable for increasing them have been proposed by many researchers. These measures include (a) choice of another sprinkle system with lower application rate and/or smaller drops, or a lower height of their fall, (b) levelling the soil surface; (c) forming surface microbasins, pits, etc; (α) ripping the soil; (e) improving soil structure thus increasing its effective porosity and subsequently permeability, and many others. It is obvious that all these measures have their own costs. So in choosing the optimal option we should evaluate both costs and revenues resulting from increasing pre-runoff application depths. Thus the application depth becomes an ecologic and economic factor for optimizing the erosion-safe sprinkle irrigation technology.

The application depth influences the cost of irrigation in a different way for various types of sprinkle systems. For sprinkle systems which operate on a position (e.g. set-move sprinkle systems) smaller application depths lead to a lesser part of the working time being used productively for direct watering the soil while more time is spent to move the system to another position. As a result the seasonal irrigated area with an appropriate soil water content for a given sprinkle system is reduced for the year under consideration. With the reduced irrigation area specific annual irrigation costs (per unit of irrigation area) are consequently higher. Smaller application depths cause also higher operating costs, such as labour and energy costs through an increased number of waterings, as well as maintenance and repair costs.

For center-pivot sprinkle systems working on a single position we have another picture. In this case smaller application depths lead mainly to much higher energy costs, so far as these systems move continuously during a watering process filled with water while set-move sprinkle systems move to another position empty. But if center-pivots work on two or more positions their specific operating costs increase sharply. For all types of irrigation systems smaller application depths with shorter irrigation intervals lead to an increase in unproductive (or very low productive) water loss through soil water evaporation.

First let us examine influence of application depths on the irrigated area netto Ω_i^{nt}.

For a given sprinkle system with a discharge Q irrigated area

netto is calculated as follows

$$\Omega_i^{nt} = \frac{Q}{q_t}\ , \text{ ha}, \qquad (3)$$

where Q = sprinkle system design capacity, l/s;
q_t = specific irrigation technological discharge, that is discharge per unit area net, or irrigation hydromodule as we call it here in Russia, l/(s·ha).

$$q_t = q_c \cdot K_t, \text{ l/(s·ha)}, \qquad (4)$$

where q_c = specific irrigation crop discharge, l/(s·ha);
K_{nt} = natural and technological coefficient.

$$q_c = \frac{D_{max}}{8.64}\ , \text{ l/(s·ha)}, \qquad (5)$$

where D_{max} = design daily irrigation requirement, mm/day.

It is worthwhile to note that the design daily irrigation requirement for a crop D_{max} depends both on the climatic conditions of the site and the adopted sprinkle irrigation technology because the latter includes the pre-runoff application depths. Recommendations on the design daily irrigation requirements available here in Russia are usually based on field experimental data obtained with maximum application depths. So some kind of correction is needed in the course of iterative optimization process of the erosion-safe sprinkle irrigation technology.

The natural and technological coefficient K_{nt} is estimated as follows

$$K_{nt} = \frac{1}{\alpha\beta\gamma\delta\varepsilon\nu} \qquad (6)$$

where α = parameter showing what part of the day the sprinkle system is able to operate (during the peak water requirement period);
β = parameter reflecting technologic losses of the working time;
γ = parameter that takes into account possible loss of the working time for operational repairs of the sprinkle system;
δ = parameter revealing possible loss of the working time due to failure of the turnouts, pumps or conveyance system;
ε = parameter that allows for drop evaporation and drift loss;
ν = parameter showing what part of the peak water requirement period could be actually used for irrigation without strong or gusty wind.

For a given type of sprinkle system, influence of the application depth on the adequately irrigated area is expressed mainly through parameter β. It can be elaborated as follows

$$\beta = \frac{t_w}{t_w + t_i} \qquad (7)$$

where t_w = duration of direct watering the soil for a technologic time;
t_i = total technologic interruption in direct watering the soil attributed to a technologic time.

$$t_i = t_{i1} + t_{i2} + t_{i3}, \qquad (8)$$

where t_{i1} = duration of interruption in direct watering the soil for a technologic time;
t_{i2} = the same for a technologic cycle attributed to a technologic time;
t_{i3} = the same for a technologic period attributed to a technologic time.

Under a technologic time we understand the least common periodically repeated technologic process that is a part of a longer technologic cycle which in its turn is a part of the most prolonged technologic period.

Multiplying numerator and denominator of the proper fraction (7) by the average effective application rate we get

$$\beta = \frac{m}{m+m_i}\ , \tag{9}$$

where m = actual application depth;
m_i = unrealized application depth that is the depth of water that could have been applied during total technologic interruption in direct watering the soil.

For example, if we compare two options of an iden-tical side-roll set-move irrigation system working on the same field with m_1 = 15 mm and m_2 = 60 mm (pre-runoff application depth in the second option is higher thanks to special measures), t_i = 60 min, ρ = 0.2 mm/min (about 0.47 iph), then the area properly irrigated in the second option will be half as much again as in the first one. For another example, if we choose a type of an irrigation system with the same discharge from two options: side roll (ρ = 0,2 mm/min, m = 30 mm, t_i = 60 min) and center-pivot (m = 30 mm, t_i = 0), then we shall find that the pivot will irrigate an area that is 40% more than the side-roll.

In general for any sprinkle system its specific farm irrigation system costs (that is costs attributed to a unity of properly irrigated area) are directly propor-tional to

$$k = (1 + \frac{m_i}{m}) \tag{10}$$

Specific annual energy used for linearly moving later-als within an irrigated area can be expessed as follows

$$e = m_s g k_r \frac{2M}{m} \tag{11}$$

where e - specific annual energy, N;
m_s - specific linear mass of a sprinkle lateral, kg/m (see Table 1);

$$m_s = \frac{M_s}{B_o}$$

where M_s - sprinkle lateral mass, kg;
B_o - effective length of the sprinkle lateral (effective length of the rain zone), m;
g - acceleration of gravity;
k_r - resistance coefficient;
M - seasonal irrigation requirement;
m - average application depth.

Table 1. Specific linear mass of some sprinkle systems

Type of sprinkle system	Specific linear mass, kg/m	
	dry	with water
Side-roll wheel-move «Volgianka»	6.8...8.4	-
Wheel-mounted sprinkle laterals driven with electric motors «Dniepr»	30	-
Hand-move KI-50-1A (except pump)	2	-
Tow-move with boom sprinklers ShD-25-300A	6.25	-
Linear-move «Kuban»-L 200/800	52	83
Linear-move «Tavria» 200/800	52.5	84
Irrigation machine carrying sprinkle lines mounted on a tractor DDA-100MA	90	92
Center-pivot «Fregat» (hydraulically moved)	32	50...55
Center-pivot «Kuban»-LC1 moved with electric motors	42...45	67...72

Similar formula like (11) can be used for center-pivots but without the coefficient 2. The factor of application depth is sure to play a more significant role in arid natural conditions and for more water-consuming crops.

We can see from the Table 1 that the specific linear dry mass for many set-move sprinkle system is several times less than that for continuous-move system. Thus the latter systems use much more energy for moving laterals filled with water as compared with the set-move system.

An approximate evaluation of influence of application depths on unproductive loss of water through evaporation from the soil surface (or very low productive) can be made with the use of a procedure described by L.G. James (1988). According to the procedure the crop coefficient K_c for the first growth stage is estimated as follows

$$K_c = a \ (ET_o)^b, \qquad (13)$$

where ET_o = potential evapotranspiration or reference crop ET;
a = coefficient from Table 2;
b = exponent from Table 2.

Values of a and b were given by L.G. James as depending on average interval of irrigation or rainfall t_w (days), which can be determined as a function of the application depth m and average daily irrigation requirement D_t (mm/day) for the period of t_w:

$$t_w = \frac{m}{D_t} . \ (t_w \geq 1) \qquad (14)$$

Calculations show through the coefficient K a steady increase in evapotranspiration with the decrease of irrigation intervals t_w as compared to the ET for an irrigation interval t_w = 7 days (Table 2).

Table 2. Increase in evapotranspiration for the first growth stage with decrease of irrigation intervals t_w (James, 1988)

t_w, days	7	6	5	4	3	2	1	0
a	0.742	0.790	0.844	0.904	0.976	1.049	1.134	1.250
b	- 0.319	- 0.288	- 0.254	- 0.216	- 0.175	- 0.119	-.030	0.125
K	1	1.16	1.26	1.44	1.66	1.95	2.43	3.44

Average daily level of Et_o during growth stage 1 is taken to be 5 mm/day.
Values of *a* and *b* for t_w < 2 days are graphically extrapolated, and for t_w = 3,5 and 6 - interpolated.

Another approach was used by Jordanian scientists (Al-Qinna, Abu-Awwad, 1998), who fitted their field experimental data with the following formula

$$E_{ws} = K_w K_t, \qquad (15)$$

where E_{ws} = average daily soil water evaporation under sprinkle irrigation, mm/day;
K_w - potential daily soil water evaporation during the day of irrigation in the experiment, mm/day;
K_t - coefficient reflecting a decline in daily soil water evaporation during days following irrigation.

$$K_t = 1-\sqrt{t_w/t_d}\ , \qquad (16)$$

where t_w - day number after irrigation (on the day of irrigation $t_w = 0$);
t_d - time period needed for the soil to become dry after irrigation (for the experiment $t_d = 5$ days).

According to a well-known model for soil water evaporation which can be found in any full enough textbook on soil physics, the time period t_d corresponds to transition of the soil water evaporation process into the third stage. In that stage soil water evaporation is very low and subsequently it can be neglected. Calculations using formula (16) also show a considerable increase in soil water evaporation under more frequent light irrigations as compared with more heavy and seldom ones (Table 3).

Table 3. Increase in soil water evaporation (K) with the decrease in irrigation intervals (t_w) according to formula (16)

t_w, days	5	4	3	2	1	0
K_t	0	0.106	0.225	0.368	0.553	1
K	1	1.20	1.43	1.71	2.07	2.67

As we can see from Tables 2 and 3, shorter irrigation intervals t_w (and smaller application depths m) may result in a considerable increase in water requirement for irrigation.

The material presented and discussed in the paper show strongly the necessity of taking into account the factor of application depths under sprinkle irrigation in any ecologic and economic optimization process for the construction and reconstruction of irrigation systems on the base of the concept of rational use of natural resources.

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